U.S. Global Change Research Program

Fourth National Climate Assessment

Volume II

Impacts, Risks, and Adaptation in the United States

Full report available online at: nca2018.globalchange.gov

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In August 2018, temperatures soared across the northwestern United States. The heat, combined with dry conditions, contributed to wildfire activity in several states and Canada. The cover shows the Howe Ridge Fire from across Lake McDonald in Montana's Glacier National Park on the night of August 12, roughly 24 hours after it was ignited by lightning. The fire spread rapidly, fueled by record-high temperatures and high winds, leading to evacuations and closures of parts of the park. The satellite image on the back cover, acquired on August 15, shows plumes of smoke from wildfires on the northwestern edge of Lake McDonald.

Wildfires impact communities throughout the United States each year. In addition to threatening individual safety and property, wildfire can worsen air quality locally and, in many cases, throughout the surrounding region, with substantial public health impacts including increased incidence of respiratory illness (Ch. 13: Air Quality, KM 2; Ch. 14: Human Health, KM 1; Ch. 26: Alaska, KM 3). As the climate warms, projected increases in wildfire frequency and area burned are expected to drive up costs associated with health effects, loss of homes and infrastructure, and fire suppression (Ch. 6: Forests, KM 1; Ch. 17: Complex Systems, Box 17.4). Increased wildfire activity is also expected to reduce the opportunity for and enjoyment of outdoor recreation activities, affecting quality of life as well as tourist economies (Ch. 7: Ecosystems, KM 3; Ch. 13: Air Quality, KM 2; Ch. 15 Tribes, KM 1; Ch. 19: Southeast, KM 3; Ch. 24: Northwest, KM 4).

Human-caused climate change, land use, and forest management influence wildfires in complex ways (Ch. 17: Complex Systems, KM 2). Over the last century, fire exclusion policies have resulted in higher fuel availability in most U.S. forests (CSSR, Ch. 8.3, KF 6). Warmer and drier conditions have contributed to an increase in the incidence of large forest fires in the western United States and Interior Alaska since the early 1980s, a trend that is expected to continue as the climate warms and the fire season lengthens (Ch. 1: Overview, Figure 1.2k; CSSR, Ch. 8.3, KF 6). The expansion of human activity into forests and other wildland areas has also increased over the past few decades. As the footprint of human settlement expands, fire risk exposure to people and property is expected to increase further (Ch. 5: Land Changes, KM 2).

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About This Report

The National Climate Assessment

The Global Change Research Act of 1990 mandates that the U.S. Global Change Research Program (USGCRP) deliver a report to Congress and the President no less than every four years that "1) integrates, evaluates, and interprets the findings of the Program . . .; 2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and 3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years."[1]

The Fourth National Climate Assessment (NCA4) fulfills that mandate in two volumes. This report, Volume II, draws on the foundational science described in Volume I, the *Climate Science Special Report* (CSSR).[2] Volume II focuses on the human welfare, societal, and environmental elements of climate change and variability for 10 regions and 18 national topics, with particular attention paid to observed and projected risks, impacts, consideration of risk reduction, and implications under different mitigation pathways. Where possible, NCA4 Volume II provides examples of actions underway in communities across the United States to reduce the risks associated with climate change, increase resilience, and improve livelihoods.

This assessment was written to help inform decision-makers, utility and natural resource managers, public health officials, emergency planners, and other stakeholders by providing a thorough examination of the effects of climate change on the United States.

Climate Science Special Report: NCA4 Volume I

The *Climate Science Special Report* (CSSR), published in 2017, serves as the first volume of NCA4. It provides a detailed analysis of how climate change is affecting the physical earth system across the United States and provides the foundational physical science upon which much of the assessment of impacts in this report is based. The CSSR integrates and evaluates current findings on climate science and discusses the uncertainties associated with these findings. It analyzes trends in climate change, both human-induced and natural, and projects major trends to the end of this century. Projected changes in temperature, precipitation patterns, sea level rise, and other climate outcomes are based on a range of scenarios widely used in the climate research community, referred to as Representative Concentration Pathways (RCPs). As an assessment and analysis of the physical science, the CSSR provides important input to the development of other parts of NCA4 and their primary focus on the human welfare, societal, economic, and environmental elements of climate change. A summary of the CSSR is provided in Chapter 2 (Our Changing Climate) of this report; the full report can be accessed at science2017.globalchange.gov.

Report Development, Review, and Approval Process

The National Oceanic and Atmospheric Administration (NOAA) served as the administrative lead agency for the preparation of this report. A Federal Steering Committee, composed of representatives from USGCRP agencies, oversaw the report's development.

A team of more than 300 federal and nonfederal experts—including individuals from federal, state, and local governments, tribes and Indigenous communities, national laboratories, universities, and the private sector—volunteered their time to produce the assessment, with input from external stakeholders at each stage of the process. A series of regional engagement workshops reached more than 1,000 individuals in over 40 cities, while listening sessions, webinars, and public comment periods provided valuable input to the authors. Participants included decision-makers from the public and private sectors, resource and environmental managers, scientists, educators, representatives from businesses and nongovernmental organizations, and the interested public.

NCA4 Volume II was thoroughly reviewed by external experts and the general public, as well as the Federal Government (that is, the NCA4 Federal Steering Committee and several rounds of technical and policy review by the 13 federal agencies of the USGCRP). An expert external peer review of the whole report was performed by an ad hoc committee of the National Academies of Sciences, Engineering, and Medicine (NASEM).[3] Additional information on the development of this assessment can be found in Appendix 1: Report Development Process.

Sources Used in This Report

The findings in this report are based on an assessment of the peer-reviewed scientific literature, complemented by other sources (such as gray literature) where appropriate. In addition, authors used well-established and carefully evaluated observational and modeling datasets, technical input reports, USGCRP's sustained assessment products, and a suite of scenario products. Each source was determined to meet the standards of the Information Quality Act (see Appendix 2: Information in the Fourth National Climate Assessment).

Sustained Assessment Products

The USGCRP's sustained assessment process facilitates and draws upon the ongoing participation of scientists and stakeholders, enabling the assessment of new information and insights as they emerge. The USGCRP led the development of two major sustained assessment products as inputs to NCA4: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*[4] and the *Second State of the Carbon Cycle Report*.[5] In addition, USGCRP agencies contributed products that improve the thoroughness of this assessment, including the U.S. Department of Agriculture's scientific assessment *Climate Change, Global Food Security, and the U.S. Food System*;[6] NOAA's Climate Resilience Tool Kit, Climate Explorer, and State Climate Summaries; the U.S. Environmental Protection Agency's updated economic impacts of climate change report;[7] and a variety of USGCRP indicators and scenario products that support the evaluation of climate-related risks (see Appendix 3: Data Tools and Scenario Products).

USGCRP Scenario Products

As part of the sustained assessment process, federal interagency groups developed a suite of high-resolution scenario products that span a range of plausible future changes (through at least 2100) in key environmental parameters. This new generation of USGCRP scenario products (hosted at https://scenarios.globalchange.gov) includes

- changes in average and extreme statistics of key climate variables (for example, temperature and precipitation),
- changes in local sea level rise along the entire U.S. coastline,
- changes in population as a function of demographic shifts and migration, and
- changes in land use driven by population changes.

USGCRP scenario products help ensure consistency in underlying assumptions across the report and therefore improve the ability to compare and synthesize results across chapters. Where possible, authors have used the range of these scenario products to frame uncertainty in future climate and associated effects as it relates to the risks that are the focus of their chapters. As discussed briefly elsewhere in this Front Matter and in more detail in Appendix 3 (Data Tools and Scenario Products), future scenarios referred to as RCPs provide the global framing for NCA4 Volumes I and II. RCPs focus on outputs (such as emissions and concentrations of greenhouse gases and particulate matter) that are in turn fed into climate models. As such, a wide range of future socioeconomic assumptions, at the global and national scale (such as population growth, technological innovation, and carbon intensity of energy mix), could be consistent with the RCPs used throughout NCA4. For this reason, further guidance on U.S. population and land-use assumptions was provided to authors. See Appendix 3: Data Tools and Scenario Products, including Table A3.1, for additional detail on these scenario products.

Guide to the Report

Summary Findings

The 12 Summary Findings represent a very high-level synthesis of the material in the underlying report. They consolidate Key Messages and supporting evidence from 16 underlying national-level topic chapters, 10 regional chapters, and 2 response chapters.

Overview

The Overview presents the major findings alongside selected highlights from NCA4 Volume II, providing a synthesis of material from the underlying report chapters.

Chapter Text

Key Messages and Traceable Accounts

Chapters are centered around Key Messages, which are based on the authors' expert judgment of the synthesis of the assessed literature. With a view to presenting technical information in a manner more accessible to a broad audience, this report aims to present findings in the context of risks to natural and/or human systems. Assessing the risks to the Nation posed by climate change and the measures that can be taken to minimize those risks helps users weigh the consequences of complex decisions.

Since risk can most meaningfully be defined in relation to objectives or societal values, Key Messages in each chapter of this report aim to provide answers to specific questions about what is at risk in a particular region or sector and in what way. The text supporting each Key Message provides evidence, discusses implications, identifies intersections between systems or cascading hazards, and points out paths to greater resilience. Where a Key Message focuses on managing risk, authors considered the following questions:

- What do we value? What is at risk?
- What outcomes do we wish to avoid with respect to these valued things?
- What do we expect to happen in the absence of adaptive action and/or mitigation?
- How bad could things plausibly get? Are there important thresholds or tipping points in the unique context of a given region, sector, and so on?

These considerations are encapsulated in a single question: What keeps you up at night? Importantly, climate is only one of many drivers of change and risk. Where possible, chapters provide information about the dominant sources of uncertainty (such as scientific uncertainty or socioeconomic factors), as well as information regarding other relevant non-climate stressors.

Each Key Message is accompanied by a Traceable Account that restates the Key Message found in the chapter text with calibrated confidence and likelihood language (see Table 1). These Traceable Accounts also document the supporting evidence and rationale the authors used in reaching their conclusions, while also providing information on sources of uncertainty. More information on Traceable Accounts is provided below.

Our Changing Climate

USGCRP oversaw the production of the *Climate Science Special Report* (CSSR): NCA4 Volume I,[2] which assesses the current state of science relating to climate change and its physical impacts. The CSSR is a detailed analysis of how climate change affects the physical earth system across the United States. It presents foundational information and projections for climate change that improve consistency across

analyses in NCA4 Volume II. The CSSR is the basis for the physical climate science summary presented in Chapter 2 (Our Changing Climate) of this report.

National Topic Chapters

The national topic chapters summarize current and future climate change related risks and what can be done to reduce those risks. These national chapters also synthesize relevant content from the regional chapters. New national topic chapters for NCA4 include Chapter 13: Air Quality; Chapter 16: Climate Effects on U.S. International Interests; and Chapter 17: Sector Interactions, Multiple Stressors, and Complex Systems.

Regional Chapters

Responding to public demand for more localized information—and because impacts and adaptation tend to be realized at a more local level—NCA4 provides greater detail in the regional chapters compared to the national topic chapters. The regional chapters assess current and future risks posed by climate change to each of NCA4's 10 regions (see Figure 1) and what can be done to minimize risk. Challenges, opportunities, and success stories for managing risk are illustrated through case studies.

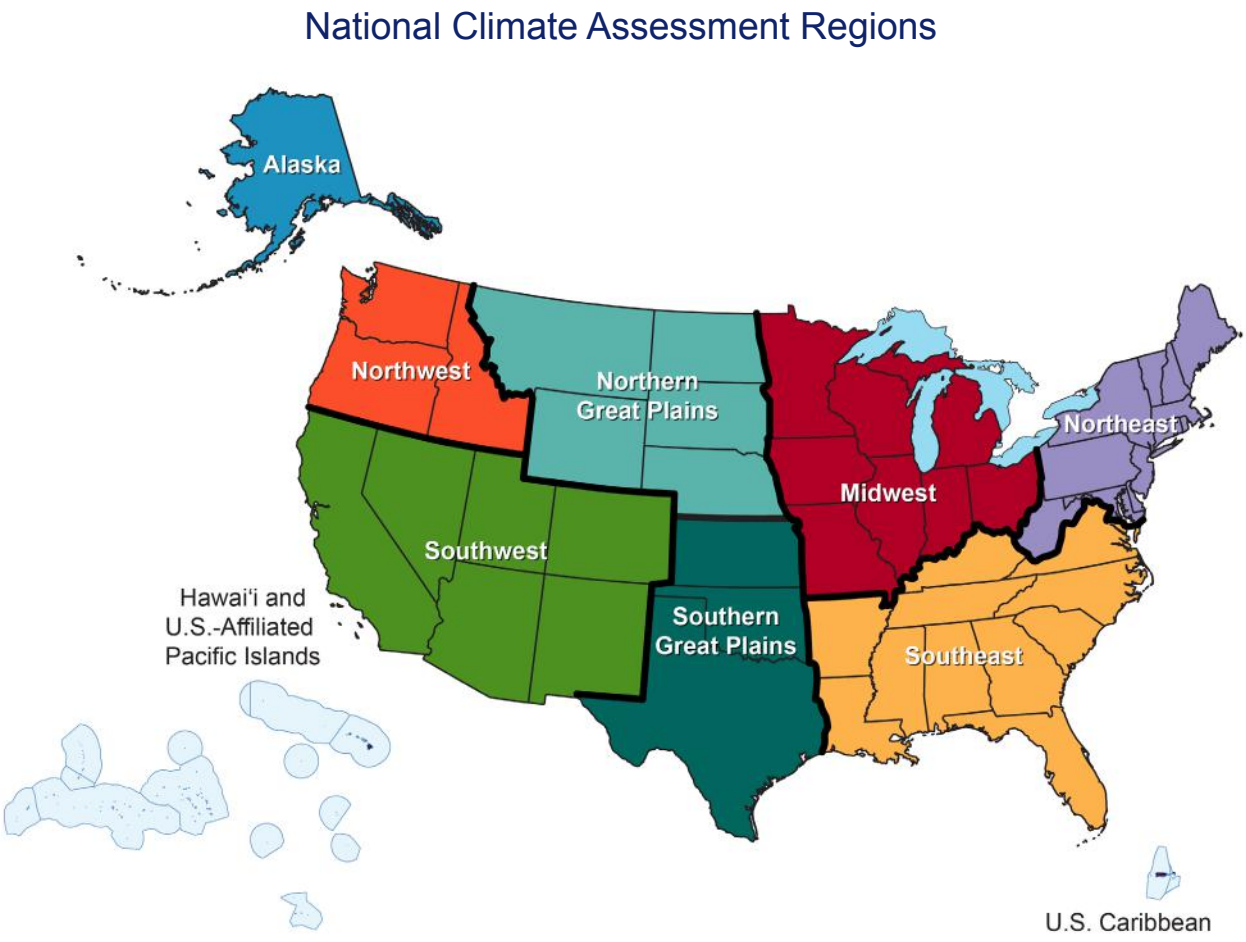

Figure 1: Map of the ten regions used throughout NCA4.

The regions defined in NCA4 are similar to those used in the Third National Climate Assessment (NCA3),[8] with these exceptions: the Great Plains region, formerly stretching from the border of Canada to the border of Mexico, is now divided into the Northern Great Plains and Southern Great Plains along the Nebraska–Kansas border; and content related to the U.S. Caribbean islands is now found in its own chapter, distinct from the Southeast region.

Response Chapters

The response chapters assess the science of adaptation and mitigation, including benefits, tradeoffs, and best practices of ongoing adaptation measures and quantification of economic damages that can be avoided by reducing greenhouse gas emissions. The National Climate Assessment does not evaluate or recommend specific policies.

Economic Estimates

To the extent possible, economic estimates in this report have been converted to 2015 dollars using the U.S. Bureau of Economic Affairs' Implicit Price Deflators for Gross Domestic Product, Table 1.1.9. For more information, please visit: https://bea.gov/national/index.htm. Where documented in the underlying literature, discount rates in specific estimates in this assessment are noted next to those projections.

Use of Scenarios

Climate modeling experts develop climate projections for a range of plausible futures. These projections capture variables such as the relationship between human choices, greenhouse gas (GHG) and particulate matter emissions, GHG concentrations in our atmosphere, and the resulting impacts, including temperature change and sea level rise. Some projections are consistent with continued dependence on fossil fuels, while others are achieved by reducing GHG emissions. The resulting range of projections reflects, in part, the uncertainty that comes with quantifying future human activities and their influence on climate.

The most recent set of climate projections developed by the international scientific community is classified under four Representative Concentration Pathways, or RCPs.[9] A wide range of future socioeconomic assumptions could be consistent with the RCPs used throughout NCA4.

NCA4 focuses on RCP8.5 as a "higher" scenario, associated with more warming, and RCP4.5 as a "lower" scenario with less warming. Other RCP scenarios (e.g., RCP2.6, a "very low" scenario) are used where instructive, such as in analyses of mitigation science issues. To promote understanding while capturing the context of the RCPs, authors use the phrases "a higher scenario (RCP8.5)" and "a lower scenario (RCP4.5)." RCP8.5 is generally associated with higher population growth, less technological innovation, and higher carbon intensity of the global energy mix. RCP4.5 is generally associated with lower population growth, more technological innovation, and lower carbon intensity of the global energy mix. NCA4 does not evaluate the feasibility of the socioeconomic assumptions within the RCPs. Future socioeconomic conditions—and especially the relationship between economic growth, population growth, and innovation—will have a significant impact on which climate change scenario is realized. The use of RCP8.5 and RCP4.5 as core scenarios is broadly consistent with the range used in NCA3.[8] For additional detail on these scenarios and what they represent, please see Appendix 3 (Data Tools and Scenario Products), as well as Chapter 4 of the *Climate Science Special Report*.[10]

Treatment of Uncertainties: Risk Framing, Confidence, and Likelihood

Risk Framing

In March 2016, NASEM convened a workshop, Characterizing Risk in Climate Change Assessments, to assist NCA4 authors in their analyses of climate-related risks across the United States.[11] To help ensure consistency and readability across chapters, USGCRP developed guidance on communicating the risks and opportunities that climate change presents, including the treatment of scientific uncertainties. Where supported by the underlying literature, authors were encouraged to

- describe the full scope of potential climate change impacts, both negative and positive, including more extreme impacts that are less likely but would have severe consequences, and communicate the range of potential impacts and their probabilities of occurrence;
- describe the likelihood of the consequences associated with the range of potential impacts, the character and quality of the consequences, both negative and positive, and the strength of available evidence;
- communicate cascading effects among and within complex systems; and
- quantify risks that could be avoided by taking action.

Additional detail on how risk is defined for this report, as well as how risk-based framing was used, is available in Chapter 1: Overview (see Box 1.2: Evaluating Risks to Inform Decisions).

Traceable Accounts: Confidence and Likelihood

Throughout NCA4's assessment of climate-related risks and impacts, authors evaluated the range of information in the scientific literature to the fullest extent possible, arriving at a series of Key Messages for each chapter. Drawing on guidance developed by the Intergovernmental Panel on Climate Change (IPCC),[12] chapter authors further described the overall reliability in their conclusions using these metrics in their chapter's Traceable Accounts:

- **Confidence** in the validity of a finding based on the type, amount, quality, strength, and consistency of evidence (such as mechanistic understanding, theory, data, models, and expert judgment); the skill, range, and consistency of model projections; and the degree of agreement within the body of literature.
- **Likelihood**, which is based on measures of uncertainty expressed probabilistically (in other words, based on statistical analysis of observations or model results or on the authors' expert judgment).

The author team's expert assessment of confidence for each Key Message is presented in the chapter's Traceable Accounts. Where the authors consider it is scientifically justified to report the likelihood of a particular impact within the range of possible outcomes, Key Messages in the Traceable Accounts also include a likelihood designation. Traceable Accounts describe the process and rationale the authors used in reaching their conclusions, as well as their confidence in these conclusions. They provide additional information about the quality of information used and allow traceability to data and resources.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, confident results, well-documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Likelihood				
Very Likely	**Likely**	**As Likely as Not**	**Unlikely**	**Very Unlikely**
≥ 9 in 10	≥ 2 in 3	= 1 in 2	≤ 1 in 3	≤ 1 in 10

Table 1: This table describes the meaning of the various categories of confidence level and likelihood assessment used in NCA4. The levels of confidence are the same as they appear in the CSSR (NCA4 Volume I). And while the likelihood scale is consistent with the CSSR, there are fewer categories, as that report relies more heavily on quantitative methods and statistics. This "binning" of likelihood is consistent with other USGCRP sustained assessment products, such as the Climate and Health Assessment[4] and NCA3.[8]

Glossary of Terms

NCA4 uses the glossary available on the USGCRP website (http://www.globalchange.gov/climate-change/glossary). It was developed for NCA3 and largely draws from the IPCC glossary of terms. Over time, it has been updated with selected new terms from more recent USGCRP assessments, including *The Impacts of Climate Change on Human Health in the United States* (https://health2016.globalchange.gov/glossary-and-acronyms) and the *Climate Science Special Report* (https://science2017.globalchange.gov/chapter/appendix-e/).

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1 Overview

Howe Ridge Fire in Montana's Glacier National Park on August 12, 2018. *Photo credit: National Park Service.*

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Introduction

Earth's climate is now changing faster than at any point in the history of modern civilization, primarily as a result of human activities. The impacts of global climate change are already being felt in the United States and are projected to intensify in the future—but the severity of future impacts will depend largely on actions taken to reduce greenhouse gas emissions and to adapt to the changes that will occur. Americans increasingly recognize the risks climate change poses to their everyday lives and livelihoods and are beginning to respond (Figure 1.1). Water managers in the Colorado River Basin have mobilized users to conserve water in response to ongoing drought intensified by higher temperatures, and an extension program in Nebraska is helping ranchers reduce drought and heat risks to their operations. The state of Hawai'i is developing management options to promote coral reef recovery from widespread bleaching events caused by warmer waters that threaten tourism, fisheries, and coastal protection from wind and waves. To address higher risks of flooding from heavy rainfall, local governments in southern Louisiana are pooling hazard reduction funds, and cities and states in the Northeast are investing in more resilient water, energy, and transportation infrastructure. In Alaska, a tribal health organization is developing adaptation strategies to address physical and mental health challenges driven by climate change and other environmental changes. As Midwestern farmers adopt new management strategies to reduce erosion and nutrient losses caused by heavier rains, forest managers in the Northwest are developing adaptation strategies in response to wildfire increases that affect human health, water resources, timber production, fish and wildlife, and recreation. After extensive hurricane damage fueled in part by a warmer atmosphere and warmer, higher seas, communities in Texas are considering ways to rebuild more resilient infrastructure. In the U.S. Caribbean, governments are developing new frameworks for storm recovery based on lessons learned from the 2017 hurricane season.

Climate-related risks will continue to grow without additional action. Decisions made today determine risk exposure for current and future generations and will either broaden or limit options to reduce the negative consequences of climate change. While Americans are responding in ways that can bolster resilience and improve livelihoods, neither global efforts to mitigate the causes of climate change nor regional efforts to adapt to the impacts currently approach the scales needed to avoid substantial damages to the U.S. economy, environment, and human health and well-being over the coming decades.

Americans Respond to the Impacts of Climate Change

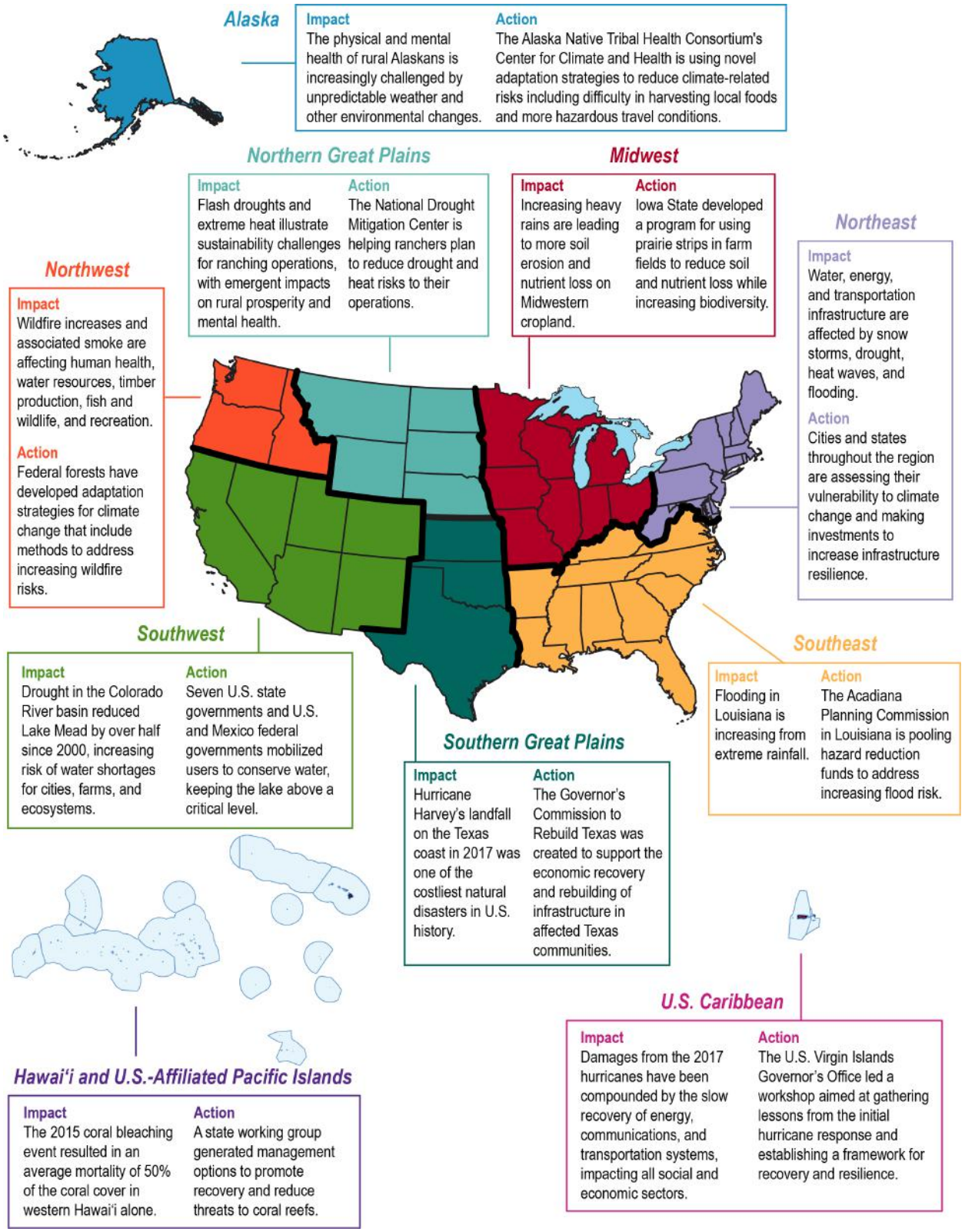


Figure 1.1: This map shows climate-related impacts that have occurred in each region since the Third National Climate Assessment in 2014 and response actions that are helping the region address related risks and costs. These examples are illustrative; they are not indicative of which impact is most significant in each region or which response action might be most effective. *Source: NCA4 Regional Chapters.*

Climate shapes where and how we live and the environment around us. Natural ecosystems, agricultural systems, water resources, and the benefits they provide to society are adapted to past climate conditions and their natural range of variability. A water manager may use past or current streamflow records to design a dam, a city could issue permits for coastal development based on current flood maps, and an electric utility or a farmer may invest in equipment suited to the current climate, all with the expectation that their investments and management practices will meet future needs.

However, the assumption that current and future climate conditions will resemble the recent past is no longer valid (Ch. 28: Adaptation, KM 2). Observations collected around the world provide significant, clear, and compelling evidence that global average temperature is much higher, and is rising more rapidly, than anything modern civilization has experienced, with widespread and growing impacts (Figure 1.2) (CSSR, Ch. 1.9). The warming trend observed over the past century can only be explained by the effects that human activities, especially emissions of greenhouse gases, have had on the climate (Ch. 2: Climate, KM 1 and Figure 2.1).

Climate change is transforming where and how we live and presents growing challenges to human health and quality of life, the economy, and the natural systems that support us. Risks posed by climate variability and change vary by region and sector and by the vulnerability of people experiencing impacts. Social, economic, and geographic factors shape the exposure of people and communities to climate-related impacts and their capacity to respond. Risks are often highest for those that are already vulnerable, including low-income communities, some communities of color, children, and the elderly (Ch. 14: Human Health, KM 2; Ch. 15: Tribes, KM 1–3; Ch. 28: Adaptation, Introduction). Climate change threatens to exacerbate existing social and economic inequalities that result in higher exposure and sensitivity to extreme weather and climate-related events and other changes (Ch. 11: Urban, KM 1). Marginalized populations may also be affected disproportionately by actions to address the underlying causes and impacts of climate change, if they are not implemented under policies that consider existing inequalities (Ch. 11: Urban, KM 4; Ch. 28: Adaptation, KM 4).

This report draws a direct connection between the warming atmosphere and the resulting changes that affect Americans' lives, communities, and livelihoods, now and in the future. It documents vulnerabilities, risks, and impacts associated with natural climate variability and human-caused climate change across the United States and provides examples of response actions underway in many communities. It concludes that *the evidence of human-caused climate change is overwhelming and continues to strengthen, that the impacts of climate change are intensifying across the country, and that climate-related threats to Americans' physical, social, and economic well-being are rising.* These impacts are projected to intensify—but how much they intensify will depend on actions taken to reduce global greenhouse gas emissions and to adapt to the risks from climate change now and in the coming decades (Ch. 28: Adaptation, Introduction; Ch. 29: Mitigation, KM 3 and 4).

Our Changing Climate: Observations, Causes, and Future Change

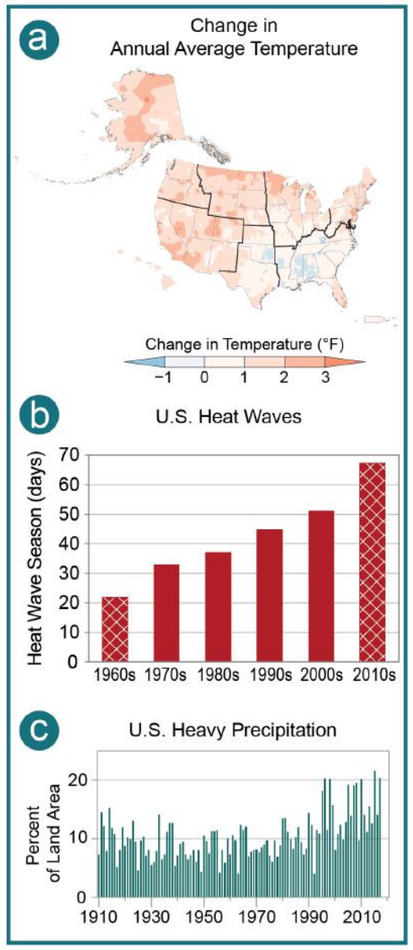
Observed Change

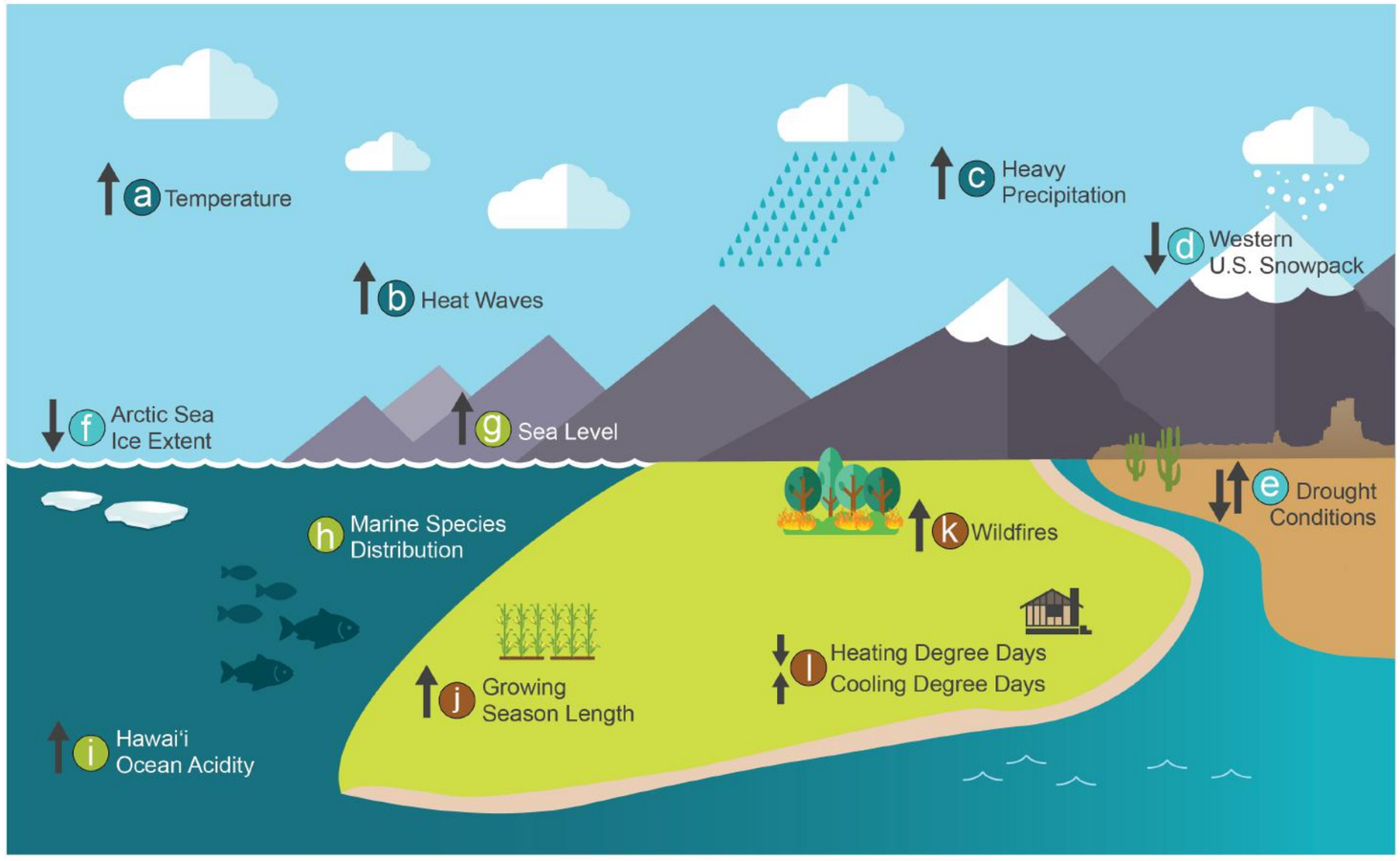
Observations from around the world show the widespread effects of increasing greenhouse gas concentrations on Earth's climate. High temperature extremes and heavy precipitation events are increasing. Glaciers and snow cover are shrinking, and sea ice is retreating. Seas are warming, rising, and becoming more acidic, and marine species are moving to new locations toward cooler waters. Flooding is becoming more frequent along the U.S. coastline. Growing seasons are lengthening, and wildfires are increasing. These and many other changes are clear signs of a warming world (Figure 1.2) (Ch. 2: Climate, Box 2.2; App. 3: Data & Scenarios, see also the USGCRP Indicators and EPA Indicators websites).

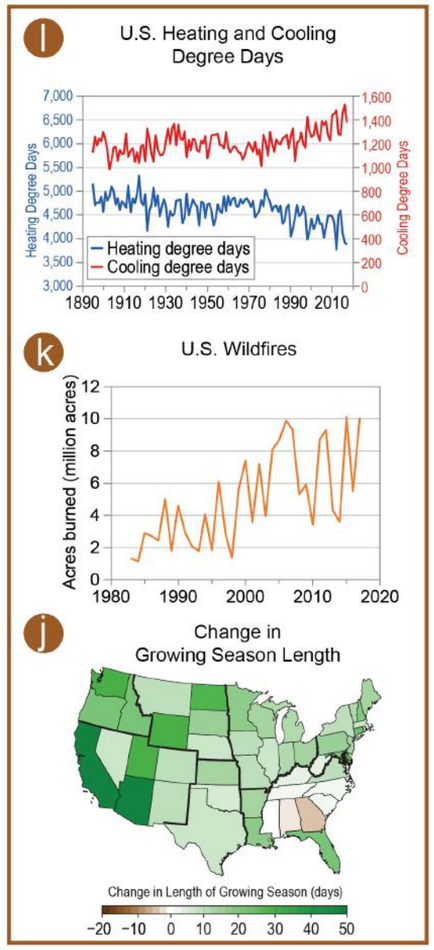
California Drought Affects Mountain Snowpack

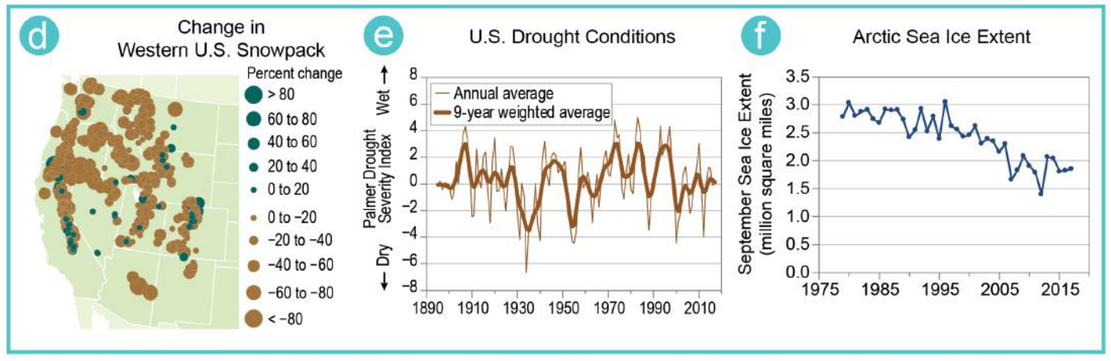
California's recent multiyear drought left Tioga Pass in the Sierra Nevada mountain range nearly snowless at the height of winter in January 2015. *Photo credit: Bartshé Miller.*

Climate Change Indicators









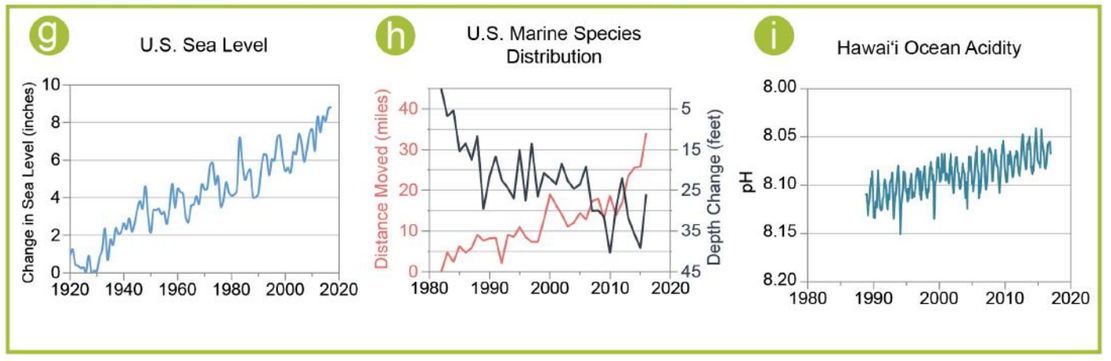


Figure 1.2: Long-term observations demonstrate the warming trend in the climate system and the effects of increasing atmospheric greenhouse gas concentrations (Ch. 2: Climate, Box 2.2). This figure shows climate-relevant indicators of change based on data collected across the United States. Upward-pointing arrows indicate an increasing trend; downward-pointing arrows indicate a decreasing trend. Bidirectional arrows (e.g., for drought conditions) indicate a lack of a definitive national trend.

(Figure caption continued on next page)

Atmosphere (a–c): (a) Annual average temperatures have increased by 1.8°F across the contiguous United States since the beginning of the 20th century; this figure shows observed change for 1986–2016 (relative to 1901–1960 for the contiguous United States and 1925–1960 for Alaska, Hawai'i, Puerto Rico, and the U.S. Virgin Islands). Alaska is warming faster than any other state and has warmed twice as fast as the global average since the mid-20th century (Ch. 2: Climate, KM 5; Ch. 26: Alaska, Background). (b) The season length of heat waves in many U.S. cities has increased by over 40 days since the 1960s. Hatched bars indicate partially complete decadal data. (c) The relative amount of annual rainfall that comes from large, single-day precipitation events has changed over the past century; since 1910, a larger percentage of land area in the contiguous United States receives precipitation in the form of these intense single-day events.

Ice, snow, and water (d–f): (d) Large declines in snowpack in the western United States occurred from 1955 to 2016. (e) While there are a number of ways to measure drought, there is currently no detectable change in long-term U.S. drought statistics using the Palmer Drought Severity Index. (f) Since the early 1980s, the annual minimum sea ice extent (observed in September each year) in the Arctic Ocean has decreased at a rate of 11%–16% per decade (Ch. 2: Climate, KM 7).

Oceans and coasts (g–i): (g) Annual median sea level along the U.S. coast (with land motion removed) has increased by about 9 inches since the early 20th century as oceans have warmed and land ice has melted (Ch. 2: Climate, KM 4). (h) Fish, shellfish, and other marine species along the Northeast coast and in the eastern Bering Sea have, on average, moved northward and to greater depths toward cooler waters since the early 1980s (records start in 1982). (i) Oceans are also currently absorbing more than a quarter of the carbon dioxide emitted to the atmosphere annually by human activities, increasing their acidity (measured by lower pH values; Ch. 2: Climate, KM 3).

Land and ecosystems (j–l): (j) The average length of the growing season has increased across the contiguous United States since the early 20th century, meaning that, on average, the last spring frost occurs earlier and the first fall frost arrives later; this map shows changes in growing season length at the state level from 1895 to 2016. (k) Warmer and drier conditions have contributed to an increase in large forest fires in the western United States and Interior Alaska over the past several decades (CSSR, Ch. 8.3). (l) Degree days are defined as the number of degrees by which the average daily temperature is higher than 65°F (cooling degree days) or lower than 65°F (heating degree days) and are used as a proxy for energy demands for cooling or heating buildings. Changes in temperatures indicate that heating needs have decreased and cooling needs have increased in the contiguous United States over the past century.

Sources: (a) adapted from Vose et al. 2017, (b) EPA, (c–f and h–l) adapted from EPA 2016, (g and center infographic) EPA and NOAA.

Causes of Change

Scientists have understood the fundamental physics of climate change for almost 200 years. In the 1850s, researchers demonstrated that carbon dioxide and other naturally occurring greenhouse gases in the atmosphere prevent some of the heat radiating from Earth's surface from escaping to space: this is known as the greenhouse effect. This natural greenhouse effect warms the planet's surface about 60°F above what it would be otherwise, creating a habitat suitable for life. Since the late 19th century, however, humans have released an increasing amount of greenhouse gases into the atmosphere through burning fossil fuels and, to a lesser extent, deforestation and land-use change. As a result, the atmospheric concentration of carbon dioxide, the largest contributor to human-caused warming, has increased by about 40% over the industrial era. This change has intensified the natural greenhouse effect, driving an increase in global surface temperatures and other widespread changes in Earth's climate that are unprecedented in the history of modern civilization.

Global climate is also influenced by natural factors that determine how much of the sun's energy enters and leaves Earth's atmosphere and by natural climate cycles that affect temperatures and weather patterns in the short term, especially regionally (see Ch. 2: Climate, Box 2.1). However, the unambiguous long-term warming trend in global average temperature over the last century cannot be explained by natural factors alone. Greenhouse gas emissions from human activities are the

only factors that can account for the observed warming over the last century; there are no credible alternative human or natural explanations supported by the observational evidence. Without human activities, the influence of natural factors alone would actually have had a slight cooling effect on global climate over the last 50 years (Ch. 2: Climate, KM 1, Figure 2.1).

Future Change

Greenhouse gas emissions from human activities will continue to affect Earth's climate for decades and even centuries. Humans are adding carbon dioxide to the atmosphere at a rate far greater than it is removed by natural processes, creating a long-lived reservoir of the gas in the atmosphere and oceans that is driving the climate to a warmer and warmer state. Some of the other greenhouse gases released by human activities, such as methane, are removed from the atmosphere by natural processes more quickly than carbon dioxide; as a result, efforts to cut emissions of these gases could help reduce the rate of global temperature increases over the next few decades. However, longer-term changes in climate will largely be determined by emissions and atmospheric concentrations of carbon dioxide and other longer-lived greenhouse gases (Ch. 2: Climate, KM 2).

Climate models representing our understanding of historical and current climate conditions are often used to project how our world will change under future conditions (see Ch. 2: Climate, Box 2.7). "Climate" is defined as weather conditions over multiple decades, and climate model projections are generally not designed to capture annual or even decadal variation in climate conditions. Instead, projections are typically used to capture long-term changes, such as how the climate system will respond to changes in greenhouse gas levels over this century. Scientists test climate models by comparing them to current observations and historical changes. Confidence in these models is based, in part, on how well they reproduce these observed changes. Climate models have proven remarkably accurate in simulating the climate change we have experienced to date, particularly in the past 60 years or so when we have greater confidence in observations (see CSSR, Ch. 4.3.1). The observed signals of a changing climate continue to become stronger and clearer over time, giving scientists increased confidence in their findings even since the Third National Climate Assessment was released in 2014.

Today, the largest uncertainty in projecting future climate conditions is the level of greenhouse gas emissions going forward. Future global greenhouse gas emissions levels and resulting impacts depend on economic, political, and demographic factors that can be difficult to predict with confidence far into the future. Like previous climate assessments, NCA4 relies on a suite of possible scenarios to evaluate the implications of different climate outcomes and associated impacts throughout the 21st century. These "Representative Concentration Pathways" (RCPs) capture a range of potential greenhouse gas emissions pathways and associated atmospheric concentration levels through 2100.

RCPs drive climate model projections for temperature, precipitation, sea level, and other variables under futures that have either lower or higher greenhouse gas emissions. RCPs are numbered according to changes in radiative forcing by 2100 relative to preindustrial conditions: +2.6, +4.5, +6.0, or +8.5 watts per square meter (W/m^2). Each RCP leads to a different

Box 1.1: Confidence and Uncertainty in Climate Science

Many of the decisions we make every day are based on less-than-perfect knowledge. For example, while GPS-based applications on smartphones can provide a travel-time estimate for our daily drive to work, an unexpected factor like a sudden downpour or fender bender might mean a ride originally estimated to be 20 minutes could actually take longer. Fortunately, even with this uncertainty we are confident that our trip is unlikely to take less than 20 minutes or more than half an hour—and we know where we are headed. We have enough information to plan our commute.

Uncertainty is also a part of science. A key goal of scientific research is to increase our confidence and reduce the uncertainty in our understanding of the world around us. Even so, there is no expectation that uncertainty can be fully eliminated, just as we do not expect a perfectly accurate estimate for our drive time each day. Studying Earth's climate system is particularly challenging because it integrates many aspects of a complex natural system as well as many human-made systems. Climate scientists find varying ranges of uncertainty in many areas, including observations of climate variables, the analysis and interpretation of those measurements, the development of new observational instruments, and the use of computer-based models of the processes governing Earth's climate system. While there is inherent uncertainty in climate science, there is high confidence in our understanding of the greenhouse effect and the knowledge that human activities are changing the climate in unprecedented ways. There is enough information to make decisions based on that understanding.

Where important uncertainties do exist, efforts to quantify and report those uncertainties can help decision-makers plan for a range of possible future outcomes. These efforts also help scientists advance understanding and ultimately increase confidence in and the usefulness of model projections. Assessments like this one explicitly address scientific uncertainty associated with findings and use specific language to express it to improve relevance to risk analysis and decision-making (see Front Matter and Box 1.2).

level of projected global temperature change; higher numbers indicate greater projected temperature change and associated impacts. The higher scenario (RCP8.5) represents a future where annual greenhouse gas emissions increase significantly throughout the 21st century before leveling off by 2100, whereas the other RCPs represent more rapid and substantial mitigation by mid-century, with greater reductions thereafter. Current trends in annual greenhouse gas emissions, globally, are consistent with RCP8.5.

Of the two RCPs predominantly referenced throughout this report, the lower scenario (RCP4.5) envisions about 85% lower greenhouse gas emissions than the higher scenario (RCP8.5) by the end of the 21st century (see Ch. 2: Climate, Figure 2.2). In some cases, throughout this report, a very low scenario (RCP2.6) that represents more immediate, substantial, and sustained emissions reductions is considered. Each RCP could be consistent with a range of underlying socioeconomic conditions or policy choices. See the Scenario Products section of Appendix 3 in this report, as well as CSSR Chapters 4.2.1 and 10.2.1 for more detail.

The effects of different future greenhouse gas emissions levels on global climate become most evident around 2050, when temperature

Projected Changes in U.S. Annual Average Temperatures

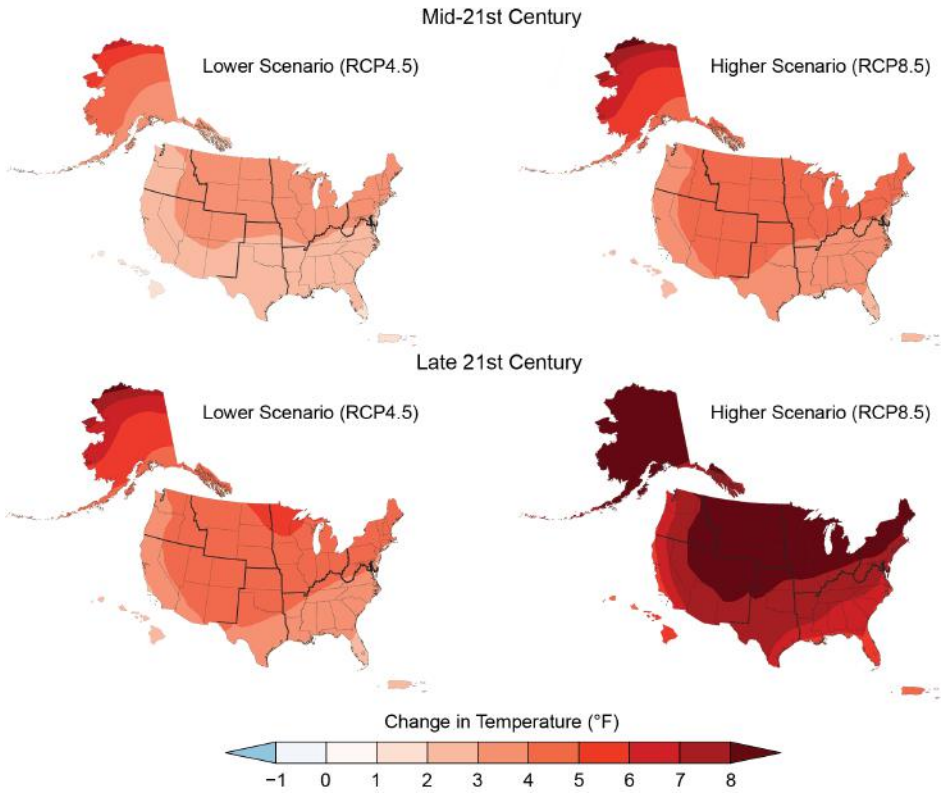


Figure 1.3: Annual average temperatures across the United States are projected to increase over this century, with greater changes at higher latitudes as compared to lower latitudes, and under a higher scenario (RCP8.5; right) than under a lower one (RCP4.5; left). This figure shows projected differences in annual average temperatures for mid-century (2036–2065; top) and end of century (2071–2100; bottom) relative to the near present (1986–2015). *From Figure 2.4, Ch. 2: Climate (Source: adapted from Vose et al. 2017).*

(Figure 1.3) (Ch. 2: Climate, Figure 2.2), precipitation, and sea level rise (Figure 1.4) (Ch. 2: Climate, Figure 2.3) projections based on each scenario begin to diverge significantly. With substantial and sustained reductions in greenhouse gas emissions (e.g., consistent with the very low scenario [RCP2.6]), the increase in global annual average temperature relative to preindustrial times could be limited to less than 3.6°F (2°C) (Ch. 2: Climate, Box 2.4; CSSR, Ch. 4.2.1). Without significant greenhouse gas mitigation, the increase in global annual average temperature could reach 9°F or more by the end of this century (Ch. 2: Climate, KM 2). For some aspects of Earth's climate system that take longer to respond to changes in atmospheric greenhouse gas concentrations, such as global sea level, some degree of long-term change will be locked in for centuries to come, regardless of the future scenario (see CSSR, Ch. 12.5.3). Early greenhouse gas emissions mitigation can reduce climate impacts in the nearer term (such as reducing the loss of arctic sea ice and the effects on species that use it) and in the longer term by avoiding critical thresholds (such as marine ice sheet instability and the resulting consequences for global sea level and coastal development; Ch. 29: Mitigation, Timing and Magnitude of Action).

Annual average temperatures in the United States are projected to continue to increase in the coming decades. Regardless of future scenario, additional increases in temperatures

Projected Relative Sea Level Change in the United States by 2100

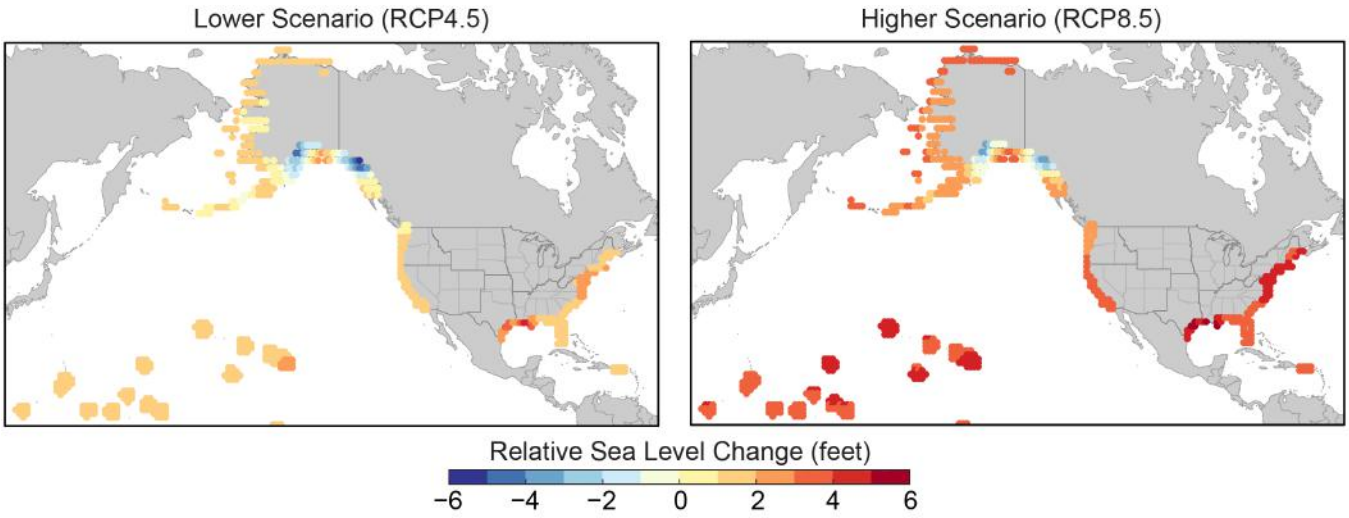


Figure 1.4: The maps show projections of change in relative sea level along the U.S. coast by 2100 (as compared to 2000) under the lower (RCP4.5) and higher (RCP8.5) scenarios (see CSSR, Ch. 12.5). Globally, sea levels will continue to rise from thermal expansion of the ocean and melting of land-based ice masses (such as Greenland, Antarctica, and mountain glaciers). Regionally, however, the amount of sea level rise will not be the same everywhere. Where land is sinking (as along the Gulf of Mexico coastline), relative sea level rise will be higher, and where land is rising (as in parts of Alaska), relative sea level rise will be lower. Changes in ocean circulation (such as the Gulf Stream) and gravity effects due to ice melt will also alter the heights of the ocean regionally. Sea levels are expected to continue to rise along almost all U.S. coastlines, and by 2100, under the higher scenario, coastal flood heights that today cause major damages to infrastructure would become common during high tides nationwide (Ch. 8: Coastal; Scenario Products section in Appendix 3). *Source: adapted from CSSR, Figure 12.4*.

across the contiguous United States of at least 2.3°F relative to 1986–2015 are expected by the middle of this century. As a result, recent record-setting hot years are expected to become common in the near future. By late this century, increases of 2.3°–6.7°F are expected under a lower scenario (RCP4.5) and 5.4°–11.0°F under a higher scenario (RCP8.5) relative to 1986–2015 (Figure 1.3) (Ch. 2: Climate, KM 5, Figure 2.4). Alaska has warmed twice as fast as the global average since the mid-20th century; this trend is expected to continue (Ch. 26: Alaska, Background).

High temperature extremes, heavy precipitation events, high tide flooding events along the U.S. coastline, ocean acidification and warming, and forest fires in the western United States and Alaska are all projected to continue to increase, while land and sea ice cover, snowpack, and surface soil moisture are expected to continue to decline in the coming decades. These and other changes are expected to increasingly impact water resources, air quality, human health, agriculture, natural ecosystems, energy and transportation infrastructure, and many other natural and human systems that support communities across the country. The severity of these projected impacts, and the risks they present to society, is greater under futures with higher greenhouse gas emissions, especially if limited or no adaptation occurs (Ch. 29: Mitigation, KM 2).

Box 1.2: Evaluating Risks to Inform Decisions

In this report, *risks* are often defined in a qualitative sense as threats to life, health and safety, the environment, economic well-being, and other things of value to society (Ch. 28: Adaptation, Introduction). In some cases, risks are described in quantitative terms: estimates of how likely a given threat is to occur (probability) and the damages that would result if it did happen (consequences). Climate change is a risk management challenge for society; it presents uncertain—and potentially severe—consequences for natural and human systems across generations. It is characterized by multiple intersecting and uncertain future hazards and, therefore, acts as a risk multiplier that interacts with other stressors to create new risks or to alter existing ones (see Ch. 17: Complex Systems, KM 1).

Current and future greenhouse gas emissions, and thus mitigation actions to reduce emissions, will largely determine future climate change impacts and risks to society. Mitigation and adaptation activities can be considered complementary strategies—mitigation efforts can reduce future risks, while adaptation can minimize the consequences of changes that are already happening as a result of past and present greenhouse gas emissions. Adaptation entails proactive decision-making and investments by individuals, businesses, and governments to counter specific risks from climate change that vary from place to place. Climate risk management includes some familiar attributes and tactics for most businesses and local governments, which often manage or design for a variety of weather-related risks, including coastal and inland storms, heat waves, threats to water availability, droughts, and floods.

Measuring risk encompasses both likelihoods and consequences of specific outcomes and involves judgments about what is of value, ranking of priorities, and cost–benefit analyses that incorporate the tradeoffs among climate and non-climate related options. This report characterizes specific risks across regions and sectors in an effort to help people assess the risks they face, create and implement a response plan, and monitor and evaluate the efficacy of a given action (see Ch. 28: Adaptation, KM 1, Figure 28.1).

Climate Change in the United States: Current and Future Risks

Some climate-related impacts, such as increasing health risks from extreme heat, are common to many regions of the United States (Ch. 14: Human Health, KM 1). Others represent more localized risks, such as infrastructure damage caused by thawing of permafrost (long-frozen ground) in Alaska or threats to coral reef ecosystems from warmer and more acidic seas in the U.S. Caribbean, as well as Hawai‘i and the U.S.-Affiliated Pacific Islands (Ch. 26: Alaska, KM 2; Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawai‘i & Pacific Islands, KM 4). Risks vary by both a community's exposure to physical climate impacts and by factors that influence its ability to respond to changing conditions and to recover from adverse weather and climate-related events such as extreme storms or wildfires (Ch. 14: Human Health, KM 2; Ch. 15: Tribes, State of the Sector, KM 1 and 2; Ch. 28: Adaptation, KM 4).

Many places are subject to more than one climate-related impact, such as extreme rainfall combined with coastal flooding, or drought coupled with extreme heat, wildfire, and flooding. The compounding effects of these impacts result in increased risks to people, infrastructure, and interconnected economic sectors (Ch. 11: Urban, KM 1). Impacts affecting

interconnected systems can cascade across sectors and regions, creating complex risks and management challenges. For example, changes in the frequency, intensity, extent, and duration of wildfires can result in a higher instance of landslides that disrupt transportation systems and the flow of goods and services within or across regions (Box 1.3). Many observed impacts reveal vulnerabilities in these interconnected systems that are expected to be exacerbated as climate-related risks intensify. Under a higher scenario (RCP8.5), it is very likely that some impacts, such as the effects of ice sheet disintegration on sea level rise and coastal development, will be irreversible for many thousands of years, and others, such as species extinction, will be permanent (Ch. 7: Ecosystems, KM 1; Ch. 9: Oceans, KM 1; Ch. 29: Mitigation, KM 2).

Economy and Infrastructure

Without more significant global greenhouse gas mitigation and regional adaptation efforts, climate change is expected to cause substantial losses to infrastructure and property and impede the rate of economic growth over this century (Ch. 4: Energy, KM 1; Ch. 8: Coastal, KM 1; Ch. 11: Urban, KM 2; Ch. 12: Transportation, KM 1; Regional Chapters 18–27). Regional economies and industries that depend on natural resources and favorable climate conditions, such as agriculture, tourism, and fisheries, are increasingly vulnerable to impacts driven by climate change (Ch. 7: Ecosystems, KM 3; Ch. 10: Agriculture, KM 1). Reliable and affordable energy supplies, which underpin virtually every sector of the economy, are increasingly at risk from climate change and weather extremes (Ch. 4: Energy,

Box 1.3: Interconnected Impacts of Climate Change

The impacts of climate change and extreme weather on natural and built systems are often considered from the perspective of individual sectors: how does a changing climate impact water resources, the electric grid, or the food system? None of these sectors, however, exists in isolation. The natural, built, and social systems we rely on are all interconnected, and impacts and management choices within one sector may have cascading effects on the others (Ch. 17: Complex Systems, KM 1).

For example, wildfire trends in the western United States are influenced by rising temperatures and changing precipitation patterns, pest populations, and land management practices. As humans have moved closer to forestlands, increased fire suppression practices have reduced natural fires and led to denser vegetation, resulting in fires that are larger and more damaging when they do occur (Figures 1.5 and 1.2k) (Ch. 6: Forests, KM 1). Warmer winters have led to increased pest outbreaks and significant tree kills, with varying feedbacks on wildfire. Increased wildfire driven by climate change is projected to increase costs associated with health effects, loss of homes and other property, wildfire response, and fuel management. Failure to anticipate these interconnected impacts can lead to missed opportunities for effectively managing risks within a single sector and may actually increase risks to other sectors. Planning around wildfire risk and other risks affected by climate change entails the challenge of accounting for all of these influences and how they interact with one another (see Ch. 17: Complex Systems, Box 17.4).

Box 1.3: Interconnected Impacts of Climate Change, *continued*

New to this edition of the NCA, Chapter 17 (Complex Systems) highlights several examples of interconnected impacts and documents how a multisector perspective and joint management of systems can enhance resilience to a changing climate. It is often difficult or impossible to quantify and predict how all relevant processes and interactions in interconnected systems will respond to climate change. Non-climate influences, such as population changes, add to the challenges of projecting future outcomes (Ch. 17: Complex Systems, KM 2). Despite these challenges, there are opportunities to learn from experience to guide future risk management decisions. Valuable lessons can be learned retrospectively: after Superstorm Sandy in 2012, for example, the mayor of New York City initiated a Climate Change Adaptation Task Force that brought together stakeholders from several sectors such as water, transportation, energy, and communications to address the interdependencies among them (Ch. 17: Complex Systems, Box 17.1, KM 3).

Wildfire at the Wildland–Urban Interface

Figure 1.5: Wildfires are increasingly encroaching on American communities, posing threats to lives, critical infrastructure, and property. In October 2017, more than a dozen fires burned through northern California, killing dozens of people and leaving thousands more homeless. Communities distant from the fires were affected by poor air quality as smoke plumes darkened skies and caused the cancellation of school and other activities across the region. (left) A NASA satellite image shows active fires on October 9, 2017. (right) The Tubbs Fire, which burned parts of Napa, Sonoma, and Lake counties, was the most destructive in California's history. It caused an estimated $1.2 billion in damages and destroyed over 5,000 structures, including 5% of the housing stock in the city of Santa Rosa. *Image credits: (left) NASA; (right) Master Sgt. David Loeffler, U.S. Air National Guard.*

KM 1). The impacts of climate change beyond our borders are expected to increasingly affect our trade and economy, including import and export prices and U.S. businesses with overseas operation and supply chains (Box 1.4) (Ch. 16: International, KM 1; Ch. 17: Complex Systems, KM 1). Some aspects of our economy may see slight improvements in a modestly warmer world. However, the continued warming that is projected to occur without significant reductions in global greenhouse gas emissions is expected to cause substantial net damage to the U.S. economy, especially in the absence of increased adaptation efforts. The potential for losses in some sectors could reach hundreds of billions of dollars per year by the end of this century (Ch. 29: Mitigation, KM 2).

Existing water, transportation, and energy infrastructure already face challenges from heavy rainfall, inland and coastal flooding, landslides, drought, wildfire, heat waves, and

other weather and climate events (Figures 1.5–1.9) (Ch. 11: Urban, KM 2; Ch. 12: Transportation, KM 1). Many extreme weather and climate-related events are expected to become more frequent and more intense in a warmer world, creating greater risks of infrastructure disruption and failure that can cascade across economic sectors (Ch. 3: Water, KM 2; Ch. 4: Energy, KM 1; Ch. 11: Urban, KM 3; Ch. 12: Transportation, KM 2). For example, more frequent and severe heat waves and other extreme events in many parts of the United States are expected to increase stresses on the energy system, amplifying the risk of more frequent and longer-lasting power outages and fuel shortages that could affect other critical sectors and systems, such as access to medical care (Ch. 17: Complex Systems, Box 17.5; Ch. 4: Energy, KM 1; Ch. 8: Coastal, KM 1; Ch. 11: Urban, KM 3; Ch. 12: Transportation, KM 3). Current infrastructure is typically designed for historical climate conditions (Ch. 12: Transportation, KM 1) and development patterns—for instance, coastal land use—generally do not account for a changing climate (Ch. 5: Land Changes, State of the Sector), resulting in increasing vulnerability to future risks from weather extremes and climate change (Ch. 11: Urban, KM 2). Infrastructure age and deterioration make failure or interrupted service from extreme weather even more likely (Ch. 11: Urban, KM 2). Climate change is expected to increase the costs of maintaining, repairing, and replacing infrastructure, with differences across regions (Ch. 12: Transportation, Regional Summary).

Recent extreme events demonstrate the vulnerabilities of interconnected economic sectors to increasing risks from climate change (see Box 1.3). In 2017, Hurricane Harvey dumped an unprecedented amount of rainfall over the greater Houston area, some of which has been attributed to human-induced climate change (Ch. 2: Climate, Box 2.5). Resulting power outages had cascading effects on critical infrastructure facilities such as hospitals and water and wastewater treatment plants. Reduced oil production and refining capacity in the Gulf of Mexico caused price spikes regionally and nationally from actual and anticipated gasoline shortages (Figure 1.6) (Ch. 17: Complex Systems, KM 1). In the U.S. Caribbean, Hurricanes Irma and Maria caused catastrophic damage to infrastructure, including the complete failure of Puerto Rico's power grid and the loss of power throughout the U.S. Virgin Islands, as well as extensive damage to the region's agricultural industry. The death toll in Puerto Rico grew in the three months following Maria's landfall on the island due in part to the lack of electricity and potable water as well as access to medical facilities and medical care (Ch. 20: U.S. Caribbean, Box 20.1, KM 5).

Climate-related risks to infrastructure, property, and the economy vary across regions. Along the U.S. coastline, public infrastructure and $1 trillion in national wealth held in coastal real estate are threatened by rising sea levels, higher storm surges, and the ongoing increase in high tide flooding (Figures 1.4 and 1.8) (Ch. 8: Coastal, KM 1). Coastal infrastructure provides critical lifelines to the rest of the country, including energy supplies and access to goods and services from overseas trade; increased damage to coastal facilities is expected to result in cascading costs and national impacts (Ch. 8: Coastal, KM 1; Ch. 4: Energy, State of the Sector, KM 1). High tide flooding is projected to become more disruptive and costlier as its frequency, depth, and inland extent grow in the coming decades. Without significant adaptation measures, many coastal cities in the

Widespread Impacts from Hurricane Harvey

Figure 1.6: Hurricane Harvey led to widespread flooding and knocked out power to 300,000 customers in Texas in 2017, with cascading effects on critical infrastructure facilities such as hospitals, water and wastewater treatment plants, and refineries. The photo shows Port Arthur, Texas, on August 31, 2017—six days after Hurricane Harvey made landfall along the Gulf Coast. *From Figure 17.2, Ch. 17: Complex Systems (Photo credit: Staff Sgt. Daniel J. Martinez, U.S. Air National Guard)*.

Flooding at Fort Calhoun Nuclear Power Plant

Figure 1.7: Floodwaters from the Missouri River surround the Omaha Public Power District's Fort Calhoun Station, a nuclear power plant just north of Omaha, Nebraska, on June 20, 2011. The flooding was the result of runoff from near-record snowfall totals and record-setting rains in late May and early June. A protective berm holding back the floodwaters from the plant failed, which prompted plant operators to transfer offsite power to onsite emergency diesel generators. Cooling for the reactor temporarily shut down, but spent fuel pools were unaffected. *From Figure 22.5, Ch. 22: N. Great Plains (Photo credit: Harry Weddington, U.S. Army Corps of Engineers).*

Norfolk Naval Base at Risk from Rising Seas

Figure 1.8: Low-lying Norfolk, Virginia, houses the world's largest naval base, which supports multiple aircraft carrier groups and is the duty station for thousands of employees. Most of the area around the base lies less than 10 feet above sea level, and local relative sea level is projected to rise between about 2.5 and 11.5 feet by the year 2100 under the Lower and Upper Bound USGCRP sea level rise scenarios, respectively (see Scenario Products section of Appendix 3 for more details on these sea level rise scenarios; see also Ch. 8: Coastal, Case Study "Key Messages in Action—Norfolk, Virginia"). *Photo credit: Mass Communication Specialist 1st Class Christopher B. Stoltz, U.S. Navy*.

Southeast are expected to experience daily high tide flooding by the end of the century (Ch. 8: Coastal, KM 1; Ch. 19: Southeast, KM 2). Higher sea levels will also cause storm surge from tropical storms to travel farther inland than in the past, impacting more coastal properties and infrastructure (Ch. 8: Coastal: KM 1; Ch. 19: Southeast, KM 2). Oil, natural gas, and electrical infrastructure located along the coasts of the Atlantic Ocean and Gulf of Mexico are at increased risk of damage from rising sea levels and stronger hurricanes; regional disruptions are expected to have national implications (Ch. 4: Energy, State of the Sector, KM 1; Ch.

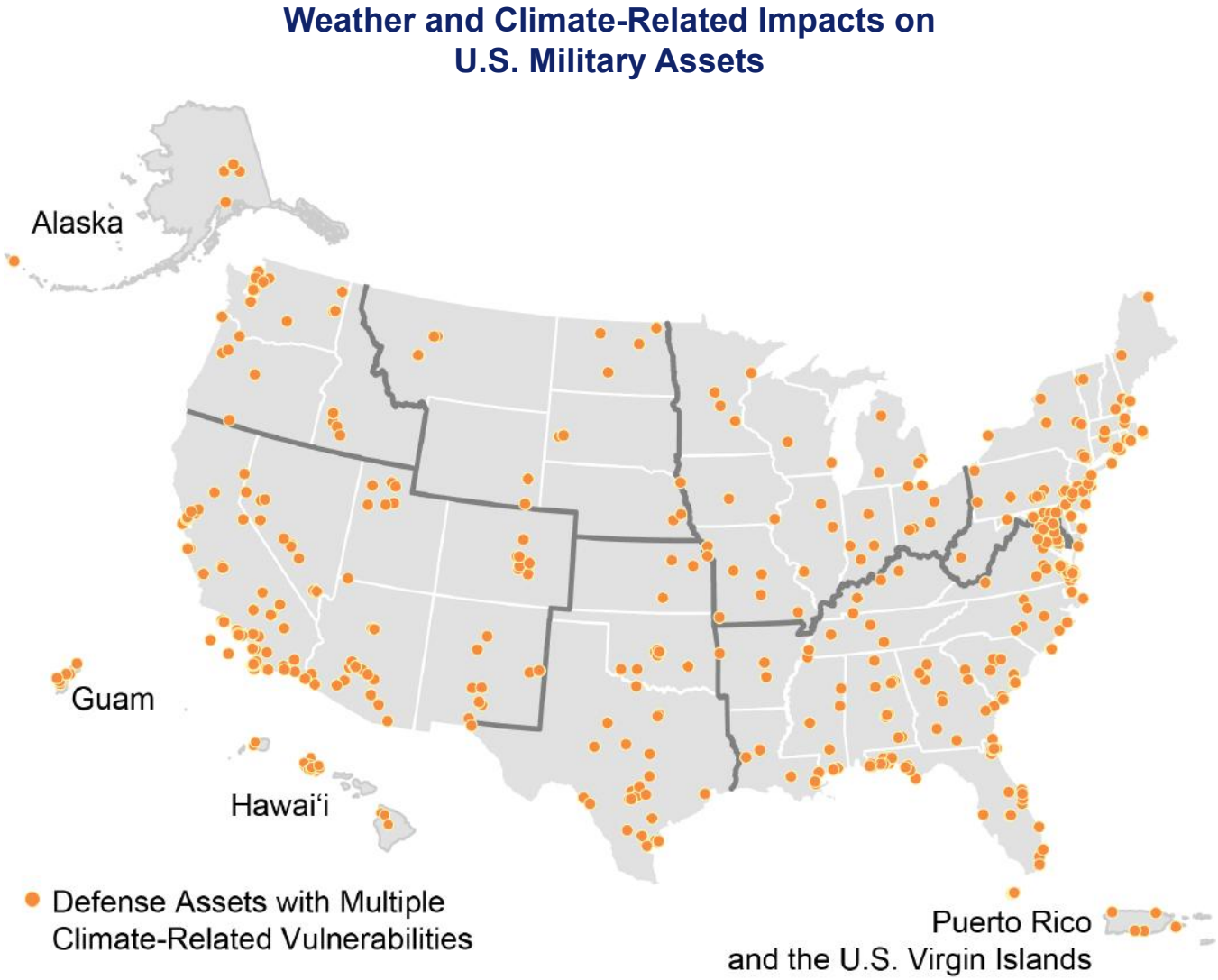


Figure 1.9: The Department of Defense (DoD) has significant experience in planning for and managing risk and uncertainty. The effects of climate and extreme weather represent additional risks to incorporate into the Department's various planning and risk management processes. To identify DoD installations with vulnerabilities to climate-related impacts, a preliminary Screening Level Vulnerability Assessment Survey (SLVAS) of DoD sites worldwide was conducted in 2015. The SLVAS responses (shown for the United States; orange dots) yielded a wide range of qualitative information. The highest number of reported effects resulted from drought (782), followed closely by wind (763) and non-storm surge related flooding (706). About 10% of sites indicated being affected by extreme temperatures (351), while flooding due to storm surge (225) and wildfire (210) affected about 6% of the sites reporting. The survey responses provide a preliminary qualitative picture of DoD assets currently affected by severe weather events as well as an indication of assets that may be affected by sea level rise in the future. *Source: adapted from Department of Defense 2018 (http://www.oea.gov/resource/2018-climate-related-risk-dod-infrastructure-initial-vulnerability-assessment-survey-slvas)*.

18: Northeast, KM 3; Ch. 19: Southeast, KM 2). Hawai'i and the U.S.-Affiliated Pacific Islands and the U.S. Caribbean also face high risks to critical infrastructure from coastal flooding, erosion, and storm surge (Ch. 4: Energy, State of the Sector; Ch. 20: U.S. Caribbean, KM 3; Ch. 27: Hawai'i & Pacific Islands, KM 3).

In the western United States, increasing wildfire is damaging ranches and rangelands as well as property in cities near the wildland–urban interface. Drier conditions are projected to increase the risk of wildfires and damage to property and infrastructure, including energy production and generation assets and the power grid (Ch. 4: Energy, KM 1; Ch. 11: Urban, Regional Summary; Ch. 24: Northwest, KM 3). In Alaska, thawing of permafrost is responsible for severe damage to roads, buildings, and pipelines that will be costly to replace, especially in remote parts of Alaska. Alaska oil and gas operations are vulnerable to thawing permafrost, sea level rise, and increased coastal exposure due to declining sea ice; however, a longer ice-free season may enhance offshore energy operations and transport (Ch. 4: Energy, State of the Sector; Ch. 26: Alaska, KM 2 and 5). These impacts are expected to grow with continued warming.

U.S. agriculture and the communities it supports are threatened by increases in temperatures, drought, heavy precipitation events, and wildfire on rangelands (Figure 1.10) (Ch. 10: Ag & Rural, KM 1 and 2, Case Study "Groundwater Depletion in the Ogallala Aquifer Region"; Ch. 23: S. Great Plains, KM 1, Case Study "The Edwards Aquifer"). Yields of major U.S. crops (such as corn, soybeans, wheat, rice, sorghum, and cotton) are expected to decline over this century as a consequence of increases in temperatures and possibly changes in water availability and disease and pest outbreaks (Ch. 10: Ag & Rural, KM 1). Increases in growing season temperatures in the Midwest are projected to be the largest contributing factor to declines in U.S. agricultural productivity (Ch. 21: Midwest, KM 1). Climate change is also expected to lead to large-scale shifts in the availability and prices of many agricultural products across the world, with corresponding impacts on U.S. agricultural producers and the U.S. economy (Ch. 16: International, KM 1).

Conservation Practices Reduce Impact of Heavy Rains

Figure 1.10: Increasing heavy rains are leading to more soil erosion and nutrient loss on midwestern cropland. Integrating strips of native prairie vegetation into row crops has been shown to reduce soil and nutrient loss while improving biodiversity. The inset shows a close-up example of a prairie vegetation strip. *From Figure 21.2, Ch. 21: Midwest (Photo credits: [main photo] Lynn Betts; [inset] Farnaz Kordbacheh).*

Extreme heat poses a significant risk to human health and labor productivity in the agricultural, construction, and other outdoor sectors (Ch. 10: Ag & Rural, KM 3). Under a higher scenario (RCP8.5), almost two billion labor hours are projected to be lost annually by 2090 from the impacts of temperature extremes, costing an estimated $160 billion in lost wages (Ch. 14: Human Health, KM 4). States within the Southeast (Ch. 19: Southeast, KM 4) and Southern Great Plains (Ch. 23: S. Great Plains, KM 4) regions are projected to experience some of the greatest impacts (see Figure 1.21).

Natural Environment and Ecosystem Services

Climate change threatens many benefits that the natural environment provides to society: safe and reliable water supplies, clean air, protection from flooding and erosion, and the use of natural resources for economic, recreational, and subsistence activities. Valued aspects of regional heritage and quality of life tied to the natural environment, wildlife, and outdoor recreation will change with the climate, and as a result, future generations can expect to experience and interact with natural systems in ways that are much different than today. Without significant reductions in greenhouse gas emissions, extinctions and transformative impacts on some ecosystems cannot be avoided, with varying impacts on the economic, recreational, and subsistence activities they support.

Changes affecting the quality, quantity, and availability of water resources, driven in part by climate change, impact people and the environment (Ch. 3: Water, KM 1). Dependable and safe water supplies for U.S. Caribbean, Hawai'i, and U.S.-Affiliated Pacific Island communities and ecosystems are threatened by rising temperatures, sea level rise, saltwater intrusion, and increased risks of drought and flooding (Ch. 3: Water, Regional Summary; Ch. 20: U.S. Caribbean, KM 1; Ch. 27: Hawai'i & Pacific Islands, KM 1). In the Midwest, the occurrence of conditions that contribute to harmful algal blooms, which can result in restrictions to water usage for drinking and recreation, is expected to increase (Ch. 3: Water, Regional Summary; Ch. 21: Midwest, KM 3). In the Southwest, water supplies for people and nature are decreasing during droughts due in part to climate change. Intensifying droughts, heavier downpours, and reduced snowpack are combining with other stressors such as groundwater depletion to reduce the future reliability of water supplies in the region, with cascading impacts on energy production and other water-dependent sectors (Ch. 3: Water, Regional Summary; Ch. 4: Energy, State of the Sector; Ch. 25: Southwest, KM 5). In the Southern Great Plains, current drought and projected increases in drought length and severity threaten the availability of water for agriculture (Figures 1.11 and 1.12) (Ch. 23: S. Great Plains, KM 1). Reductions in mountain snowpack and shifts in snowmelt timing are expected to reduce hydropower production in the Southwest and the Northwest (Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM 5). Drought is expected to threaten oil and gas drilling and refining as well as thermoelectric power plants that rely on a steady supply of water for cooling (Ch. 4: Energy, State of the Sector, KM 1; Ch. 22: N. Great Plains, KM 4; Ch. 23: S. Great Plains, KM 2; Ch. 25: Southwest, KM 5).

Tourism, outdoor recreation, and subsistence activities are threatened by reduced snowpack, increases in wildfire activity, and

Impacts of Drought on Texas Agriculture

Figure 1.11: Soybeans in Texas experience the effects of drought in August 2013. During 2010–2015, a multiyear regional drought severely affected agriculture in the Southern Great Plains. One prominent impact was the reduction of irrigation water released for farmers on the Texas coastal plains. *Photo credit: Bob Nichols, USDA*.

Desalination Plants Can Reduce Impacts from Drought in Texas

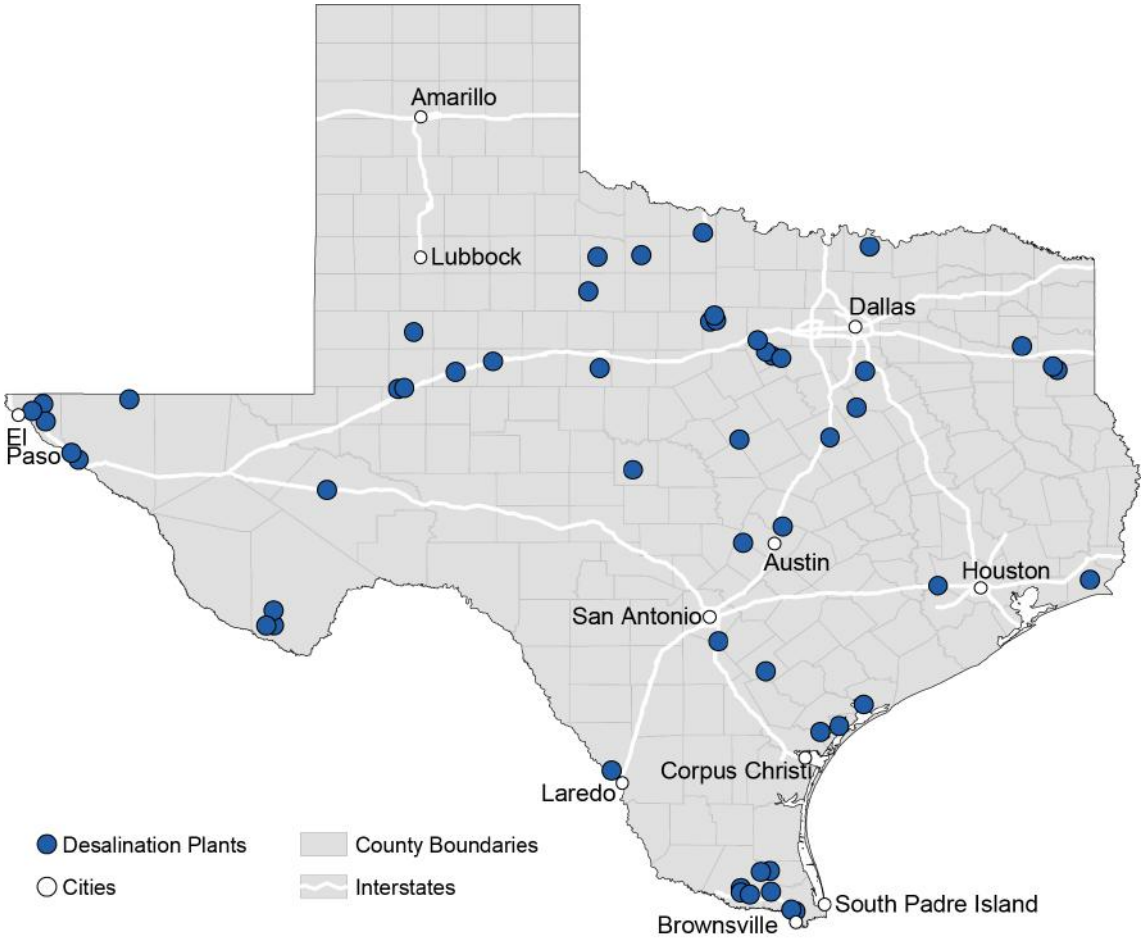


Figure 1.12: Desalination activities in Texas are an important contributor to the state's efforts to meet current and projected water needs for communities, industry, and agriculture. The state's 2017 Water Plan recommended an expansion of desalination to help reduce longer-term risks to water supplies from drought, higher temperatures, and other stressors. There are currently 44 public water supply desalination plants in Texas. *From Figure 23.8, Ch. 23: S. Great Plains (Source: adapted from Texas Water Development Board 2017)*.

other stressors affecting ecosystems and natural resources (Figures 1.2d, 1.2k, and 1.13) (Ch. 7: Ecosystems, KM 3). Increasing wildfire frequency (Ch. 19: Southeast, Case Study "Prescribed Fire"), pest and disease outbreaks (Ch. 21: Midwest, Case Study "Adaptation in Forestry"), and other stressors are projected to reduce the ability of U.S. forests to support recreation as well as economic and subsistence activities (Ch. 6: Forests, KM 1 and 2; Ch. 19: Southeast, KM 3; Ch. 21: Midwest, KM 2). Increases in wildfire smoke events driven by climate change are expected to reduce the amount and quality of time spent in outdoor activities (Ch. 13: Air Quality, KM 2; Ch. 24: Northwest, KM 4). Projected declines in snowpack in the western United States and shifts to more precipitation falling as rain than snow in the cold season in many parts of the central and eastern United States are expected to adversely impact the winter recreation industry (Ch. 18: Northeast, KM 1; Ch. 22: N. Great Plains, KM 3; Ch. 24: Northwest, KM 1, Box 24.7). In the Northeast, activities that rely on natural snow and ice cover may not be economically viable by the end of the century without significant reductions in global greenhouse gas emissions (Ch. 18: Northeast, KM 1). Diminished

Razor Clamming on the Washington Coast

Figure 1.13: Razor clamming draws crowds on the coast of Washington State. This popular recreation activity is expected to decline due to ocean acidification, harmful algal blooms, warmer temperatures, and habitat degradation. *From Figure 24.7, Ch. 24: Northwest (Photo courtesy of Vera Trainer, NOAA).*

snowpack, increased wildfire, pervasive drought, flooding, ocean acidification, and sea level rise directly threaten the viability of agriculture, fisheries, and forestry enterprises on tribal lands across the United States and impact tribal tourism and recreation sectors (Ch. 15: Tribes, KM 1).

Climate change has already had observable impacts on biodiversity and ecosystems throughout the United States that are expected to continue. Many species are shifting their ranges (Figure 1.2h), and changes in the timing of important biological events (such as migration and reproduction) are occurring in response to climate change (Ch. 7: Ecosystems, KM 1). Climate change is also aiding the spread of invasive species (Ch. 21: Midwest, Case Study "Adaptation in Forestry"; Ch. 22: N. Great Plains, Case Study "Crow Nation and the Spread of Invasive Species"), recognized as a major driver of biodiversity loss and substantial ecological and economic costs globally (Ch. 7: Ecosystems, Invasive Species). As environmental conditions change further, mismatches between species and the availability of the resources they need to survive are expected to occur (Ch. 7: Ecosystems, KM 2). Without significant reductions in global greenhouse gas emissions, extinctions and transformative impacts on some ecosystems cannot be avoided in the long term (Ch. 9: Oceans, KM 1). While some new opportunities may emerge from ecosystem changes, economic and recreational opportunities and cultural heritage based around historical use of species or natural resources in many areas are at risk (Ch. 7: Ecosystems, KM 3; Ch. 18: Northeast, KM 1 and 2, Box 18.6).

Ocean warming and acidification pose high and growing risks for many marine organisms, and the impacts of climate change on ocean ecosystems are expected to lead to reductions in important ecosystem services such as aquaculture, fishery productivity, and recreational opportunities (Ch 9: Oceans, KM 2). While climate change impacts on ocean ecosystems are widespread, the scope of ecosystem impacts occurring in tropical and polar areas is greater than anywhere else in the world. Ocean warming is already leading to reductions in vulnerable coral reef and sea ice habitats that support the livelihoods of many communities (Ch. 9: Oceans, KM 1). Decreasing sea ice extent in the Arctic represents a direct loss of important habitat for marine mammals, causing declines in their populations (Figure 1.2f) (Ch. 26: Alaska, Box 26.1). Changes in spring ice melt have affected the ability of coastal communities in Alaska to meet their walrus harvest needs in recent years (Ch. 26: Alaska, KM 1). These changes are expected to continue as sea ice declines further (Ch. 2: Climate, KM 7). In the tropics, ocean warming has already led to widespread coral reef bleaching and/or outbreaks of coral diseases off the coastlines of Puerto Rico, the U.S. Virgin Islands, Florida, and

Severe Coral Bleaching Projected for Hawai‘i and the U.S.-Affiliated Pacific Islands

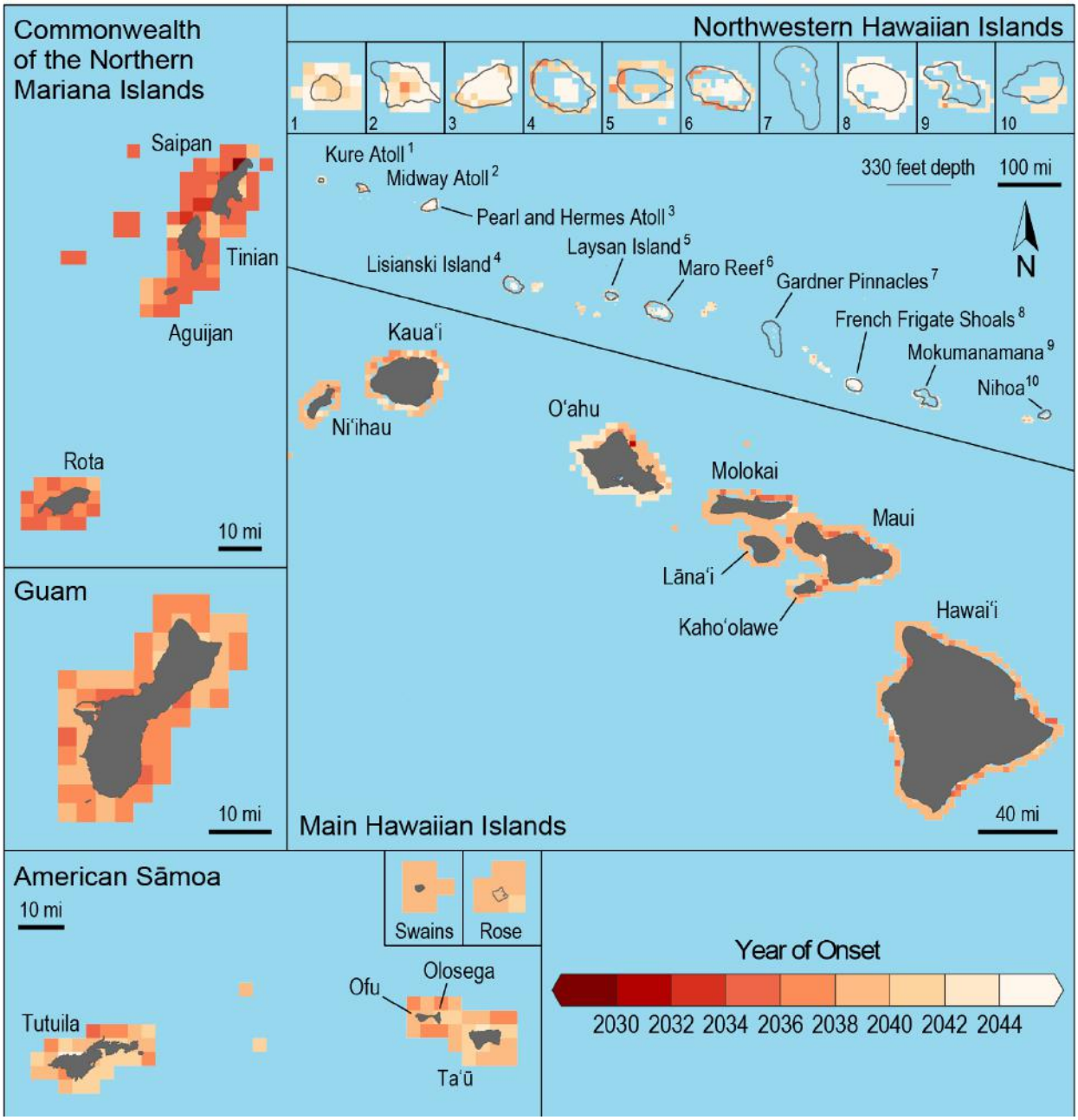


Figure 1.14: The figure shows the years when severe coral bleaching is projected to occur annually in the Hawai‘i and U.S.-Affiliated Pacific Islands region under a higher scenario (RCP8.5). Darker colors indicate earlier projected onset of coral bleaching. Under projected warming of approximately 0.5°F per decade, all nearshore coral reefs in the region will experience annual bleaching before 2050. *From Figure 27.10, Ch. 27: Hawai‘i & Pacific Islands (Source: NOAA).*

Hawai‘i and the U.S.-Affiliated Pacific Islands (Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawai‘i & Pacific Islands, KM 4). By mid-century, widespread coral bleaching is projected to occur annually in Hawai‘i and the U.S.-Affiliated Pacific Islands (Figure 1.14). Bleaching and ocean acidification are expected to result in loss of reef structure, leading to lower fisheries yields and loss of coastal protection and habitat, with impacts on tourism and livelihoods

in both regions (Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawai'i & Pacific Islands, KM 4). While some targeted response actions are underway (Figure 1.15), many impacts, including losses of unique coral reef and sea ice ecosystems, can only be avoided by significantly reducing global greenhouse gas emissions, particularly carbon dioxide (Ch. 9: Oceans, KM 1).

Human Health and Well-Being

Higher temperatures, increasing air quality risks, more frequent and intense extreme weather and climate-related events, increases in coastal flooding, disruption of ecosystem services, and other changes increasingly threaten the health and well-being of the American people, particularly populations that are already vulnerable. Future climate change is expected to further disrupt many areas of life, exacerbating existing challenges and revealing new risks to health and prosperity.

Rising temperatures pose a number of threats to human health and quality of life (Figure 1.16). High temperatures in the summer are linked directly to an increased risk of illness and death, particularly among older adults, pregnant women, and children (Ch. 18: Northeast, Box 18.3). With continued warming, cold-related deaths are projected to decrease and

Promoting Coral Reef Recovery

Figure 1.15: Examples of coral farming in the U.S. Caribbean and Florida demonstrate different types of structures used for growing fragments from branching corals. Coral farming is a strategy meant to improve the reef community and ecosystem function, including for fish species. The U.S. Caribbean Islands, Florida, Hawai'i, and the U.S.-Affiliated Pacific Islands face similar threats from coral bleaching and mortality due to warming ocean surface waters and ocean acidification. Degradation of coral reefs is expected to negatively affect fisheries and the economies that depend on them as habitat is lost in both regions. While coral farming may provide some targeted recovery, current knowledge and efforts are not nearly advanced enough to compensate for projected losses from bleaching and acidification. *From Figure 20.11, Ch. 20: U.S. Caribbean (Photo credits: [top left] Carlos Pacheco, U.S. Fish and Wildlife Service; [bottom left] NOAA; [right] Florida Fish and Wildlife).*

Projected Change in Very Hot Days by 2100 in Phoenix, Arizona

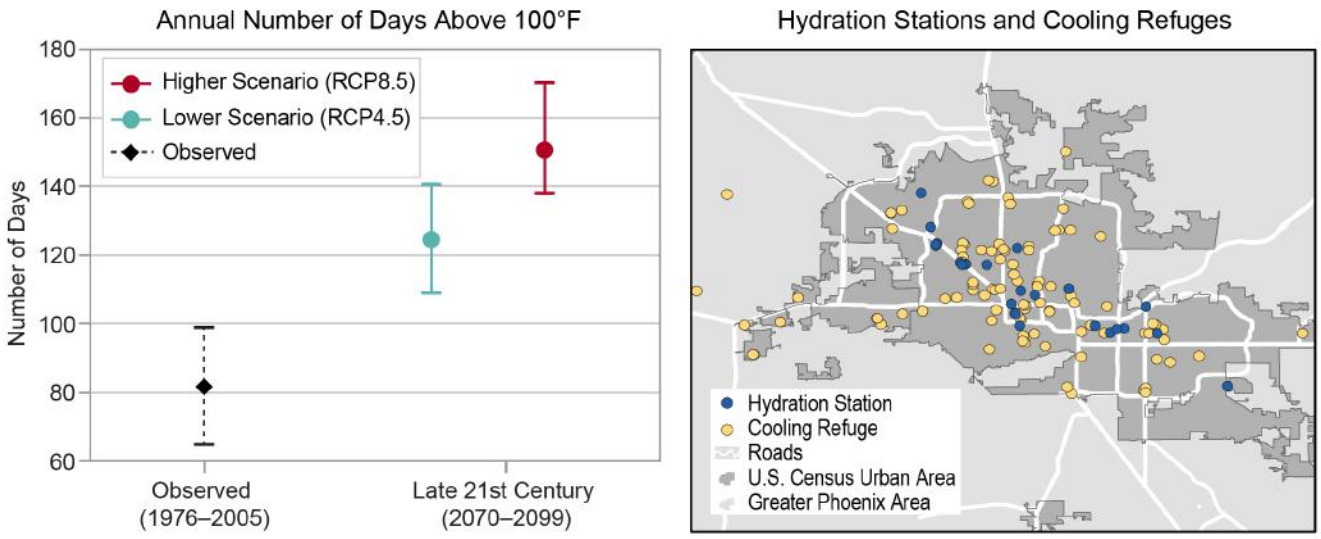


Figure 1.16: (left) The chart shows the average annual number of days above 100°F in Phoenix, Arizona, for 1976–2005, and projections of the average number of days per year above 100°F through the end of the 21st century (2070–2099) under the lower (RCP4.5) and higher (RCP8.5) scenarios. Dashed lines represent the 5th–95th percentile range of annual observed values. Solid lines represent the 5th–95th percentile range of projected model values. (right) The map shows hydration stations and cooling refuges (cooled indoor locations that provide water and refuge from the heat during the day) in Phoenix in August 2017. Such response measures for high heat events are expected to be needed at greater scales in the coming years if the adverse health effects of more frequent and severe heat waves are to be minimized. *Sources: (left) NOAA NCEI, CICS-NC, and LMI; (right) adapted from Southwest Cities Heat Refuges (a project by Arizona State University's Resilient Infrastructure Lab), available at http://www.coolme.today/#phoenix. Data provided by Andrew Fraser and Mikhail Chester, Arizona State University.*

heat-related deaths are projected to increase. In most regions, the increases in heat-related deaths are expected to outpace the reductions in cold-related deaths (Ch. 14: Human Health, KM 1). Rising temperatures are expected to reduce electricity generation capacity while increasing energy demands and costs, which can in turn lead to power outages and blackouts (Ch. 4: Energy, KM 1; Ch. 11: Urban, Regional Summary, Figure 11.2). These changes strain household budgets, increase people's exposure to heat, and limit delivery of medical and social services. Risks from heat stress are higher for people without access to housing with sufficient insulation or air conditioning (Ch. 11: Urban, KM 1).

Changes in temperature and precipitation can increase air quality risks from wildfire and ground-level ozone (smog). Projected increases in wildfire activity due to climate change would further degrade air quality, resulting in increased health risks and impacts on quality of life (Ch. 13: Air Quality, KM 2; Ch. 14: Human Health, KM 1). Unless counteracting efforts to improve air quality are implemented, climate change is expected to worsen ozone pollution across much of the country, with adverse impacts on human health (Figure 1.21) (Ch. 13: Air Quality, KM 1). Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can also increase exposure to airborne pollen allergens. The frequency and severity of allergic illnesses, including asthma and hay fever, are expected to increase as a result of a changing climate (Ch. 13: Air Quality, KM 3).

Rising air and water temperatures and changes in extreme weather and climate-related events are expected to increase exposure to waterborne and foodborne diseases, affecting

food and water safety. The geographic range and distribution of disease-carrying insects and pests are projected to shift as climate changes, which could expose more people in North America to ticks that carry Lyme disease and mosquitoes that transmit viruses such as West Nile, chikungunya, dengue, and Zika (Ch. 14: Human Health, KM 1; Ch. 16: International, KM 4).

Mental health consequences can result from exposure to climate- or extreme weather-related events, some of which are projected to intensify as warming continues (Ch. 14: Human Health, KM 1). Coastal city flooding as a result of sea level rise and hurricanes, for example, can result in forced evacuation, with adverse effects on family and community stability as well as mental and physical health (Ch. 11: Urban, KM 1). In urban areas, disruptions in food supply or safety related to extreme weather or climate-related events are expected to disproportionately impact those who already experience food insecurity (Ch. 11: Urban, KM 3).

Indigenous peoples have historical and cultural relationships with ancestral lands, ecosystems, and culturally important species that are threatened by climate change (Ch. 15: Tribes, KM 1; Ch. 19: Southeast, KM 4, Case Study "Mountain Ramps"; Ch. 24: Northwest, KM 5). Climate change is expected to compound existing physical health issues in Indigenous communities, in part due to the loss of traditional foods and practices, and in some cases, the mental stress from permanent community displacement (Ch. 14: Human Health, KM 2; Ch. 15: Tribes, KM 2). Throughout the United States, Indigenous peoples are considering or actively pursuing relocation as an adaptation strategy in response to climate-related disasters, more frequent flooding, loss of land due to erosion, or as livelihoods are compromised by ecosystem shifts linked to climate change (Ch. 15: Tribes, KM 3). In Louisiana, a federal grant is being used to relocate the tribal community of Isle de Jean Charles in response to severe land loss, sea level rise, and coastal flooding (Figure 1.17) (Ch. 19: Southeast, KM 2, Case Study "A Lesson Learned for Community Resettlement"). In Alaska, coastal

Community Relocation—Isle de Jean Charles, Louisiana

Figure 1.17: (left) A federal grant is being used to relocate the tribal community of Isle de Jean Charles, Louisiana, in response to severe land loss, sea level rise, and coastal flooding. *From Figure 15.3, Ch. 15: Tribes (Photo credit: Ronald Stine)*. (right) As part of the resettlement of the tribal community of Isle de Jean Charles, residents are working with the Lowlander Center and the State of Louisiana to finalize a plan that reflects the desires of the community. *From Figure 15.4, Ch. 15: Tribes (Photo provided by Louisiana Office of Community Development)*.

Adaptation Measures in Kivalina, Alaska

Figure 1.18: A rock revetment was installed in the Alaska Native Village of Kivalina in 2010 to reduce increasing risks from erosion. A new rock revetment wall has a projected lifespan of 15 to 20 years. *From Figure 15.3, Ch. 15: Tribes (Photo credit: ShoreZone. Creative Commons License CC BY 3.0: https://creativecommons.org/licenses/by/3.0/legalcode)*. The inset shows a close-up of the rock wall in 2011. *Photo credit: U.S. Army Corps of Engineers–Alaska District.*

Native communities are already experiencing heightened erosion driven by declining sea ice, rising sea levels, and warmer waters (Figure 1.18). Coastal and river erosion and flooding in some cases will require parts of communities, or even entire communities, to relocate to safer terrain (Ch. 26: Alaska, KM 2). Combined with other stressors, sea level rise, coastal storms, and the deterioration of coral reef and mangrove ecosystems put the long-term habitability of coral atolls in the Hawai'i and U.S.-Affiliated Pacific Islands region at risk, introducing issues of sovereignty, human and national security, and equity (Ch. 27: Hawai'i & Pacific Islands, KM 6).

Reducing the Risks of Climate Change

Climate change is projected to significantly affect human health, the economy, and the environment in the United States, particularly in futures with high greenhouse gas emissions and limited or no adaptation. Recent findings reinforce the fact that without substantial and sustained reductions in greenhouse gas emissions and regional adaptation efforts, there will be substantial and far-reaching changes over the course of the 21st century with negative consequences for a large majority of sectors, particularly towards the end of the century.

The impacts and costs of climate change are already being felt in the United States, and changes in the likelihood or severity of some recent extreme weather events can now be

Box 1.4: How Climate Change Around the World Affects the United States

The impacts of changing weather and climate patterns beyond U.S. international borders affect those living in the United States, often in complex ways that can generate both challenges and opportunities. The International chapter (Ch. 16), new to this edition of the NCA, assesses our current understanding of how global climate change, natural variability, and associated extremes are expected to impact—and in some cases are already impacting—U.S. interests both within and outside of our borders.

Current and projected climate-related impacts on our economy include increased risks to overseas operations of U.S. businesses, disruption of international supply chains, and shifts in the availability and prices of commodities. For example, severe flooding in Thailand in 2011 disrupted the supply chains for U.S. electronics manufacturers (Ch. 16: International, Figure 16.1). U.S. firms are increasingly responding to climate-related risks, including through their financial disclosures and partnerships with environmental groups (Ch. 16: International, KM 1).

Impacts from climate-related events can also undermine U.S. investments in international development by slowing or reversing social and economic progress in developing countries, weakening foreign markets for U.S. exports, and increasing the need for humanitarian assistance and disaster relief efforts. Predictive tools can help vulnerable countries anticipate natural disasters, such as drought, and manage their impacts. For example, the United States and international partners created the Famine Early Warning Systems Network (FEWS NET), which helped avoid severe food shortages in Ethiopia during a historic drought in 2015 (Ch. 16: International, KM 2).

Natural variability and changes in climate increase risks to our national security by affecting factors that can exacerbate conflict and displacement outside of U.S. borders, such as food and water insecurity and commodity price shocks. More directly, our national security is impacted by damage to U.S. military assets such as roads, runways, and waterfront infrastructure from extreme weather and climate-related events (Figures 1.8 and 1.9). The U.S. military is working to both fully understand these threats and incorporate projected climate changes into long-term planning. For example, the Department of Defense has performed a comprehensive scenario-driven examination of climate risks from sea level rise to all of its coastal military sites, including atolls in the Pacific Ocean (Ch. 16: International, KM 3).

Finally, the impacts of climate change are already affecting the ecosystems that span our Nation's borders and the communities that rely on them. International frameworks for the management of our shared resources continue to be restructured to incorporate risks from these impacts. For example, a joint commission that implements water treaties between the United States and Mexico is exploring adaptive water management strategies that account for the effects of climate change and natural variability on Colorado River water (Ch. 16: International, KM 4).

attributed with increasingly higher confidence to human-caused warming (see CSSR, Ch. 3). Impacts associated with human health, such as premature deaths due to extreme temperatures and poor air quality, are some of the most substantial (Ch. 13: Air Quality, KM 1; Ch. 14: Human Health, KM 1 and 4; Ch 29: Mitigation, KM 2). While many sectors face large economic risks from climate change, other impacts can have significant implications for societal or cultural resources. Further, some impacts will very likely be irreversible for thousands of

years, including those to species, such as corals (Ch. 9: Oceans, KM 1; Ch. 27: Hawai'i & Pacific Islands, KM 4), or that involve the crossing of thresholds, such as the effects of ice sheet disintegration on accelerated sea level rise, leading to widespread effects on coastal development lasting thousands of years (Ch. 29: Mitigation, KM 2).

Future impacts and risks from climate change are directly tied to decisions made in the present, both in terms of mitigation to reduce emissions of greenhouse gases (or remove carbon dioxide from the atmosphere) and adaptation to reduce risks from today's changed climate conditions and prepare for future impacts. Mitigation and adaptation activities can be considered complementary strategies—mitigation efforts can reduce future risks, while adaptation actions can minimize the consequences of changes that are already happening as a result of past and present greenhouse gas emissions.

Many climate change impacts and economic damages in the United States can be substantially reduced through global-scale reductions in greenhouse gas emissions complemented by regional and local adaptation efforts (Ch 29: Mitigation, KM 4). Our understanding of the magnitude and timing of risks that can be avoided varies by sector, region, and assumptions about how adaptation measures change the exposure and vulnerability of people, livelihoods, ecosystems, and infrastructure. Acting sooner rather than later generally results in lower costs overall for both adaptation and mitigation efforts and can offer other benefits in the near term (Ch. 29: Mitigation, KM 3).

Since the Third National Climate Assessment (NCA3) in 2014, a growing number of states, cities, and businesses have pursued or expanded upon initiatives aimed at reducing greenhouse gas emissions, and the scale of adaptation implementation across the country has increased. However, these efforts do not yet approach the scale needed to avoid substantial damages to the economy, environment, and human health expected over the coming decades (Ch. 28: Adaptation, KM 1; Ch. 29: Mitigation, KM 1 and 2).

Mitigation

Many activities within the public and private sectors aim for or have the effect of reducing greenhouse gas emissions, such as the increasing use of natural gas in place of coal or the expansion of wind and solar energy to generate electricity. Fossil fuel combustion accounts for approximately 85% of total U.S. greenhouse gas emissions, with agriculture, land-cover change, industrial processes, and methane from fossil fuel extraction and processing as well as from waste (including landfills, wastewater treatment, and composting) accounting for most of the remainder. A number of efforts exist at the federal level to promote low-carbon energy technologies and to increase soil and forest carbon storage.

State, local, and tribal government approaches to mitigating greenhouse gas emissions include comprehensive emissions reduction strategies as well as sector- and technology-specific policies (see Figure 1.19). Since NCA3, private companies have increasingly reported their greenhouse gas emissions, announced emissions reductions targets, implemented actions to achieve those targets, and, in some cases, even put an internal price on carbon. Individuals and other organizations are also making choices every day to reduce their carbon footprints.

Mitigation-Related Activities at State and Local Levels

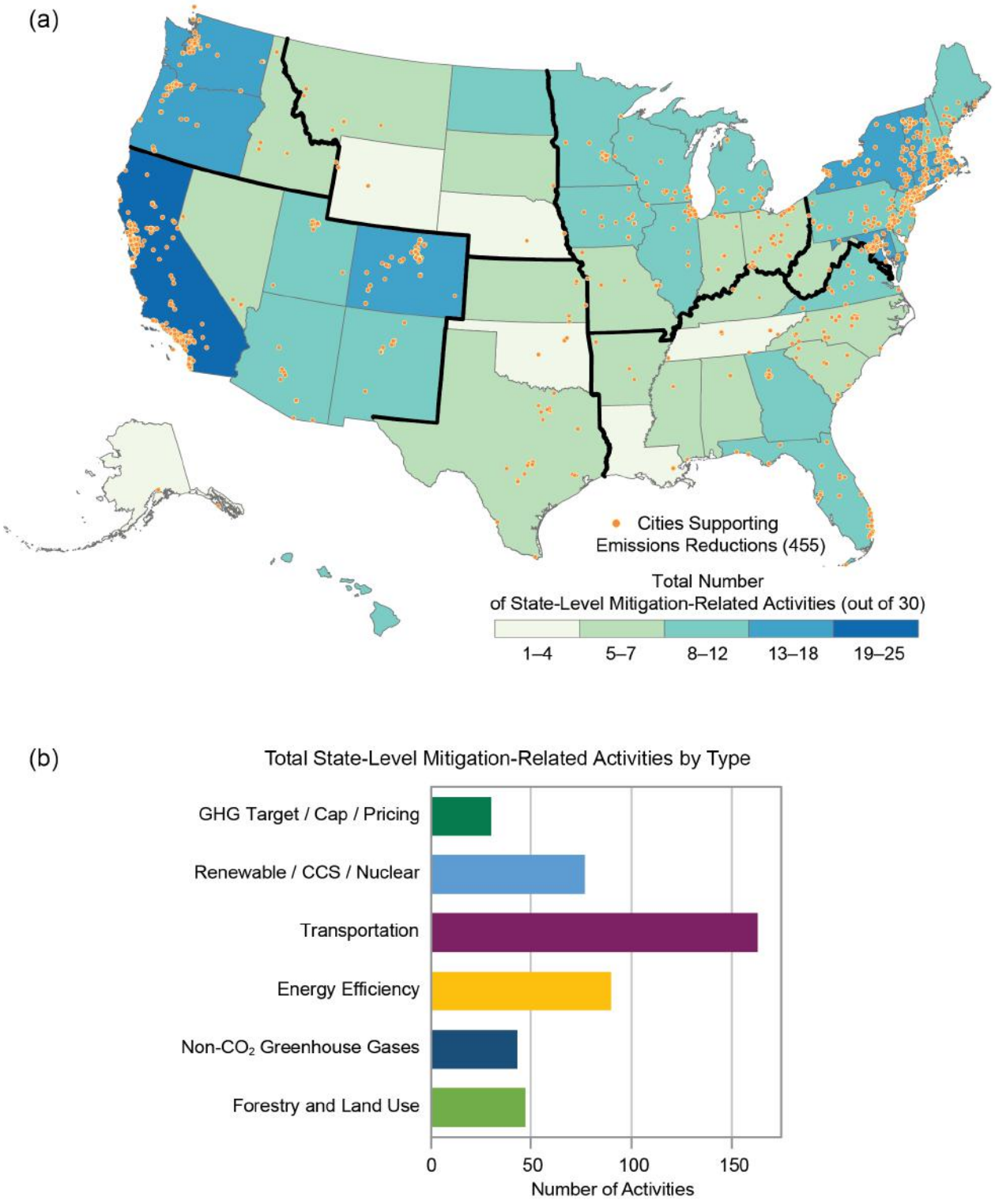


Figure 1.19: (a) The map shows the number of mitigation-related activities at the state level (out of 30 illustrative activities) as well as cities supporting emissions reductions; (b) the chart depicts the type and number of activities by state. Several territories also have a variety of mitigation-related activities, including American Sāmoa, the Federated States of Micronesia, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. *From Figure 29.1, Ch. 29: Mitigation (Sources: [a] EPA and ERT, Inc. [b] adapted from America's Pledge 2017)*.

Market forces and technological change, particularly within the electric power sector, have contributed to a decline in U.S. greenhouse gas emissions over the past decade. In 2016, U.S. emissions were at their lowest levels since 1994. Power sector emissions were 25% below 2005 levels in 2016, the largest emissions reduction for a sector of the American economy over this time. This decline was in large part due to increases in natural gas and renewable energy generation, as well as enhanced energy efficiency standards and programs (Ch. 4: Energy, KM 2). Given these advances in electricity generation, transmission, and distribution, the largest annual sectoral emissions in the United States now come from transportation. As of the writing of this report, business-as-usual (as in, no new policies) projections of U.S. carbon dioxide and other greenhouse gas emissions show flat or declining trajectories over the next decade with a central estimate of about 15% to 20% reduction below 2005 levels by 2025 (Ch. 29: Mitigation, KM 1).

Recent studies suggest that some of the indirect effects of mitigation actions could significantly reduce—or possibly even completely offset—the potential costs associated with cutting greenhouse gas emissions. Beyond reduction of climate pollutants, there are many benefits, often immediate, associated with greenhouse gas emissions reductions, such as improving air quality and public health, reducing crop damages from ozone, and increasing energy independence and security through increased reliance on domestic sources of energy (Ch. 13: Air Quality, KM 4; Ch. 29: Mitigation, KM 4).

Adaptation

Many types of adaptation actions exist, including changes to business operations, hardening infrastructure against extreme weather, and adjustments to natural resource management strategies. Achieving the benefits of adaptation can require upfront investments to achieve longer-term savings, engaging with different stakeholder interests and values, and planning under uncertainty. In many sectors, adaptation can reduce the cost of climate impacts by more than half (Ch. 28: Adaptation, KM 4; Ch. 29: Mitigation, KM 4).

At the time of NCA3's release in 2014, its authors found that risk assessment and planning were underway throughout the United States but that on-the-ground implementation was limited. Since then, the scale and scope of adaptation implementation has increased, including by federal, state, tribal, and local agencies as well as business, academic, and nonprofit organizations (Figure 1.20). While the level of implementation is now higher, it is not yet common nor uniform across the United States, and the scale of implementation for some effects and locations is often considered inadequate to deal with the projected scale of climate change risks. Communities have generally focused on actions that address risks from current climate variability and recent extreme events, such as making buildings and other assets incrementally less sensitive to climate impacts. Fewer communities have focused on actions to address the anticipated scale of future change and emergent threats, such as reducing exposure by preventing building in high-risk locations or retreating from at-risk coastal areas (Ch. 28: Adaptation, KM 1).

Many adaptation initiatives can generate economic and social benefits in excess of their costs in both the near and long term (Ch. 28: Adaptation, KM 4). Damages to infrastructure, such as road and rail networks, are particularly

Figure 1.20: Adaptation entails a continuing risk management process. With this approach, individuals and organizations become aware of and assess risks and vulnerabilities from climate and other drivers of change, take actions to reduce those risks, and learn over time. The gray arced lines compare the current status of implementing this process with the status reported by the Third National Climate Assessment in 2014; darker color indicates more activity. *From Figure 28.1, Ch. 28: Adaptation (Source: adapted from National Research Council, 2010. Used with permission from the National Academies Press, © 2010, National Academy of Sciences. Image credits, clockwise from top: National Weather Service; USGS; Armando Rodriguez, Miami-Dade County; Dr. Neil Berg, MARISA; Bill Ingalls, NASA).*

sensitive to adaptation assumptions, with proactive measures that account for future climate risks estimated to be capable of reducing damages by large fractions. More than half of damages to coastal property are estimated to be avoidable through adaptation measures such as shoreline protection and beach replenishment (Ch. 29: Mitigation, KM 4). Considerable guidance is available on actions whose benefits exceed their costs in some sectors (such as adaptation responses to storms and rising seas in coastal zones, to riverine and extreme precipitation flooding, and for agriculture at the farm level), but less so on other actions (such as those aimed at addressing risks to health, biodiversity, and ecosystems services) that may provide significant benefits but are not as well understood (Ch. 28: Adaptation, KM 4).

Effective adaptation can also enhance social welfare in many ways that can be difficult to quantify, including improving economic opportunity, health, equity, national security,

education, social connectivity, and sense of place, while safeguarding cultural resources and enhancing environmental quality. Aggregating these benefits into a single monetary value is not always the best approach, and more fundamentally, communities may value benefits differently. Considering various outcomes separately in risk management processes can facilitate participatory planning processes and allow for a specific focus on equity. Prioritizing adaptation actions for populations that face higher risks from climate change, including low-income and marginalized communities, may prove more equitable and lead, for instance, to improved infrastructure in their communities and increased focus on efforts to promote community resilience that can improve their capacity to prepare for, respond to, and recover from disasters (Ch. 28: Adaptation, KM 4).

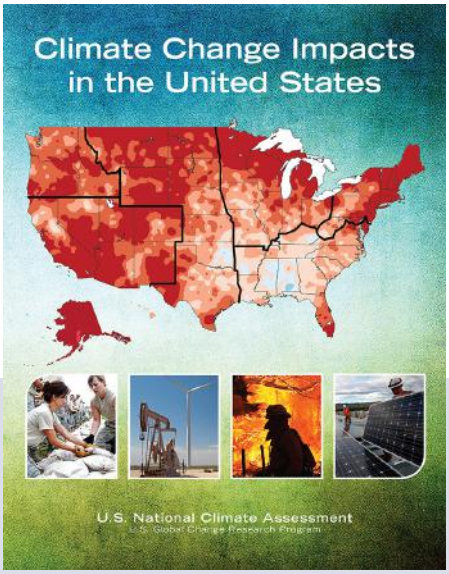
A significant portion of climate risk can be addressed by integrating climate adaptation into existing investments, policies, and practices. Integration of climate adaptation into decision processes has begun in many areas including financial risk reporting, capital investment planning, engineering standards, military planning, and disaster risk management. A growing number of jurisdictions address climate risk in their land-use, hazard mitigation, capital improvement, and transportation plans, and a small number of cities explicitly link their coastal and hazard mitigation plans using analysis of future climate risks. However, over the course of this century and especially under a higher scenario (RCP8.5), reducing the risks of climate change may require more significant changes to policy and regulations at all scales, community planning, economic and financial systems, technology applications, and ecosystems (Ch. 28: Adaptation, KM 5).

Some sectors are already taking actions that go beyond integrating climate risk into current practices. Faced with substantial climate-induced changes in the future, including new invasive species and shifting ranges for native species, ecosystem managers have already begun to adopt new approaches such as assisted migration and development of wildlife corridors (Ch. 7: Ecosystems, KM 2). Many millions of Americans live in coastal areas threatened by sea level rise; in all but the very lowest sea level rise projections, retreat will become an unavoidable option in some areas along the U.S. coastline (Ch. 8: Coastal, KM 1). The Federal Government has granted funds for the relocation of some communities, including the Biloxi-Chitimacha-Choctaw Tribe from Isle de Jean Charles in Louisiana (Figure 1.17). However, the potential need for millions of people and billions of dollars of coastal infrastructure to be relocated in the future creates challenging legal, financial, and equity issues that have not yet been addressed (Ch. 28: Adaptation, KM 5).

In some areas, lack of historical or current data to inform policy decisions can be a limitation to assessments of vulnerabilities and/or effective adaptation planning. For this National Climate Assessment, this was particularly the case for some aspects of the Alaska, U.S. Caribbean, and Hawai'i and U.S.-Affiliated Pacific Islands regions. In many instances, relying on Indigenous knowledges is among the only current means of reconstructing what has happened in the past. To help communities across the United States learn from one another in their efforts to build resilience to a changing climate, this report highlights common climate-related risks and possible response actions across all regions and sectors.

What Has Happened Since the Last National Climate Assessment?

Our understanding of and experience with climate science, impacts, risks, and adaptation in the United States have grown significantly since the Third National Climate Assessment (NCA3), advancing our knowledge of key processes in the earth system, how human and natural forces are changing them, what the implications are for society, and how we can respond.



Key Scientific Advances

Detection and Attribution: Significant advances have been made in the attribution of the human influence for individual climate and weather extreme events (see CSSR, Chs. 3, 6, 7, and 8).

Extreme Events and Atmospheric Circulation: How climate change may affect specific types of extreme events in the United States and the extent to which atmospheric circulation in the midlatitudes is changing or is projected to change, possibly in ways not captured by current climate models, are important areas of research where scientific understanding has advanced (see CSSR, Chs. 5, 6, 7, and 9).

Localized Information: As computing resources have grown, projections of future climate from global models are now being conducted at finer scales (with resolution on the order of 15 miles), providing more realistic characterization of intense weather systems, including hurricanes. For the first time in the NCA process, sea level rise projections incorporate geographic variation based on factors such as local land subsidence, ocean currents, and changes in Earth's gravitational field (see CSSR, Chs. 9 and 12).

Ocean and Coastal Waters: Ocean acidification, warming, and oxygen loss are all increasing, and scientific understanding of the severity of their impacts is growing. Both oxygen loss and acidification may be magnified in some U.S. coastal waters relative to the global average, raising the risk of serious ecological and economic consequences (see CSSR, Chs. 2 and 13).

Rapid Changes for Ice on Earth: New observations from many different sources confirm that ice loss across the globe is continuing and, in many cases, accelerating. Since NCA3, Antarctica and Greenland have continued to lose ice mass, with mounting evidence that mass loss is accelerating. Observations continue to show declines in the volume of

mountain glaciers around the world. Annual September minimum sea ice extent in the Arctic Ocean has decreased at a rate of 11%–16% per decade since the early 1980s, with accelerating ice loss since 2000. The annual sea ice extent minimum for 2016 was the second lowest on record; the sea ice minimums in 2014 and 2015 were also among the lowest on record (see CSSR, Chs. 1, 11, and 12).

Potential Surprises: Both large-scale shifts in the climate system (sometimes called "tipping points") and compound extremes have the potential to generate outcomes that are difficult to anticipate and may have high consequences. The more the climate changes, the greater the potential for these surprises (see CSSR, Ch. 15).

Extreme Events

Climate change is altering the characteristics of many extreme weather and climate-related events. Some extreme events have already become more frequent, intense, widespread, or of longer duration, and many are expected to continue to increase or worsen, presenting substantial challenges for built, agricultural, and natural systems. Some storm types such as hurricanes, tornadoes, and winter storms are also exhibiting changes that have been linked to climate change, although the current state of the science does not yet permit detailed understanding (see CSSR, Executive Summary). Individual extreme weather and climate-related events—even those that have not been clearly attributed to climate change by scientific analyses—reveal risks to society and vulnerabilities that mirror those we expect in a warmer world. Non-climate stressors (such as land-use changes and shifting demographics) can also amplify the damages associated with extreme events. The National Oceanic and Atmospheric Administration estimates that the United States has experienced 44 billion-dollar weather and climate disasters since 2015 (through April 6, 2018), incurring costs of nearly $400 billion (https://www.ncdc.noaa.gov/billions/).

Hurricanes: The 2017 Atlantic Hurricane season alone is estimated to have caused more than $250 billion in damages and over 250 deaths throughout the U.S. Caribbean, Southeast, and Southern Great Plains. More than 30 inches of rain fell during Hurricane Harvey, affecting 6.9 million people. Hurricane Maria's high winds caused widespread devastation to Puerto Rico's transportation, agriculture, communication, and energy infrastructure. Extreme rainfall of up to 37 inches caused widespread flooding and mudslides across the island. The interruption to commerce and standard living conditions will be sustained for a long period while much of Puerto Rico's infrastructure is rebuilt. Hurricane Irma destroyed 25% of buildings in the Florida Keys.

Damage from Hurricane Maria in San Juan, Puerto Rico

Photo taken during a reconnaissance flight of the island on September 23, 2017. *Photo credit: Sgt. Jose Ahiram Diaz-Ramos, Puerto Rico National Guard.*

Floods: In August 2016, a historic flood resulting from 20 to 30 inches of rainfall over several days devastated a large area of southern Louisiana, causing over $10 billion in damages and 13 deaths. More than 30,000 people were rescued from floodwaters that damaged or destroyed more than 50,000 homes, 100,000 vehicles, and 20,000 businesses. In June 2016, torrential rainfall caused destructive flooding throughout many West Virginia towns, damaging thousands of homes and businesses and causing considerable loss of life. More than 1,500 roads and bridges were damaged or destroyed. The 2015–2016 El Niño poured 11 days of record-setting rainfall on Hawai'i, causing severe urban flooding.

Drought: In 2015, drought conditions caused about $5 billion in damages across the Southwest and Northwest, as well as parts of the Northern Great Plains. California experienced the most severe drought conditions. Hundreds of thousands of acres of farmland remained fallow, and excess groundwater pumping was required to irrigate existing agricultural interests. Two years later, in 2017, extreme drought caused $2.5 billion in agricultural damages across the Northern Great Plains. Field crops, including wheat, were severely damaged, and the lack of feed for cattle forced ranchers to sell off livestock.

Wildfires: During the summer of 2015, over 10.1 million acres—an area larger than the entire state of Maryland—burned across the United States, surpassing 2006 for the highest

The Deadly Carr Fire

The Carr Fire (as seen over Shasta County, California, on August 4, 2018) damaged or destroyed more than 1,500 structures and resulted in several fatalities. *Photo credit: Sgt. Lani O. Pascual, U.S. Army National Guard.*

annual total of U.S. acreage burned since record keeping began in 1960. These wildfire conditions were exacerbated by the preceding drought conditions in several states. The most extensive wildfires occurred in Alaska, where 5 million acres burned within the state. In Montana, wildfires burned in excess of 1 million acres. The costliest wildfires occurred in California, where more than 2,500 structures were destroyed by the Valley and Butte Fires; insured losses alone exceeded $1 billion. In October 2017, a historic firestorm damaged or destroyed more than 15,000 homes, businesses, and other structures across California (see Figure 1.5). The Tubbs, Atlas, Nuns, and Redwood Valley Fires caused a total of 44 deaths, and their combined destruction represents the costliest wildfire event on record.

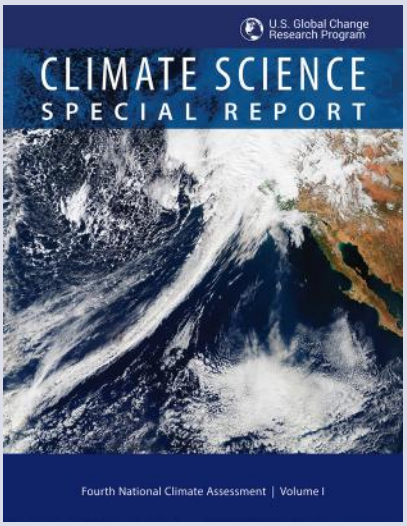
Tornadoes: In March 2017, a severe tornado outbreak caused damage across much of the Midwest and into the Northeast. Nearly 1 million customers lost power in Michigan alone due to sustained high winds, which affected several states from Illinois to New York.

Heat Waves: Honolulu experienced 24 days of record-setting heat during the 2015–2016 El Niño event. As a result, the local energy utility issued emergency public service announcements to curtail escalating air conditioning use that threatened the electrical grid.

New Aspects of This Report

Hundreds of states, counties, cities, businesses, universities, and other entities are implementing actions that build resilience to climate-related impacts and risks, while also aiming to reduce greenhouse gas emissions. Many of these actions have been informed by new climate-related tools and products developed through the U.S. Global Change Research Program (USGCRP) since NCA3 (see Appendix 3: Scenario Products and Data Tools); we briefly highlight a few of them here. In addition, several structural changes have been introduced to the report and new methods used in response to stakeholder needs for more localized information and to address key gaps identified in NCA3. The Third National Climate Assessment remains a valuable and relevant resource—this report expands upon our knowledge and experience as presented four years ago.

Climate Science Special Report: Early in the development of NCA4, experts and Administration officials recognized that conducting a comprehensive physical science assessment (Volume I) in advance of an impacts assessment (Volume II) would allow one to inform the other. The *Climate Science Special Report*, released in November 2017, is Volume I of NCA4 and represents the most thorough and up-to-date assessment of climate science in the United States and underpins the findings of this report; its findings are summarized in Chapter 2 (Our Changing Climate). See the "Key Scientific Advances" section in this box and Box 2.3 in Chapter 2 for more detail.



Scenario Products: As described in more detail in Appendix 3 (Data Tools & Scenario Products), federal interagency groups developed a suite of high-resolution scenario products that span a range of plausible future changes in key environmental variables through at least 2100. These USGCRP scenario products help ensure consistency across the report and improve the ability to synthesize across chapters. Where possible, authors have used these scenario products to frame uncertainty in future climate as it relates to the risks that are the focus of their chapters. In addition, the Indicators Interagency Working Group has developed an Indicators platform that uses observations or calculations to monitor conditions or trends in the earth system, just as businesses might use the unemployment index as an indicator of economic conditions (see Figure 1.2 and https://www.globalchange.gov/browse/indicators).

Localized Information: With the increased focus on local and regional information in NCA4, USGCRP agencies developed two additional products that not only inform this assessment but can serve as valuable decision-support tools. The first are the State Climate Summaries—a peer-reviewed collection of climate change information covering all ten NCA4 regions at the state level. In addition to standard data on observed and projected climate change, each State Climate Summary contains state-specific changes and their related impacts as well as a suite of complementary graphics (stateclimatesummaries.globalchange.gov). The second product is the U.S. Climate Resilience Toolkit (https://toolkit.climate.gov/), which offers data-driven tools, information, and subject-matter expertise from across the Federal Government in one easy-to-use location, so Americans are better able to understand the climate-related risks and opportunities impacting their communities and can make more informed decisions on how to respond. In particular, the case studies showcase examples of climate change impacts and accompanying response actions that complement those presented in Figure 1.1 and allow communities to learn how to build resilience from one another.

New Chapters: In response to public feedback on NCA3 and input solicited in the early stages of this assessment, a number of significant structural changes have been made. Most fundamentally, the balance of the report's focus has shifted from national-level chapters to regional chapters in response to a growing desire for more localized information on impacts. Building on this theme, the Great Plains chapter has been split into Northern and Southern chapters (Chapters 22 and 23) along the Kansas–Nebraska border. In addition, the U.S. Caribbean is now featured as a separate region in this report (Chapter 20), focusing on the unique impacts, risks, and response capabilities in Puerto Rico and the U.S. Virgin Islands.

Public input also requested greater international context in the report, which has been addressed through two new additions. A new chapter focuses on topics including the effects of climate change on U.S. trade and businesses, national security, and U.S. humanitarian assistance and disaster relief (Chapter 16). A new international appendix (Appendix 4) presents a number of illustrative examples of how other countries have conducted national climate assessments, putting our own effort into a global context.

Given recent scientific advances, some emerging topics warranted a more visible platform in NCA4. A new chapter on Air Quality (Chapter 13) examines how traditional air pollutants are affected by climate change. A new chapter on Sector Interactions, Multiple Stressors, and Complex Systems (Chapter 17) evaluates climate-related risks to interconnected human and natural systems that are increasingly vulnerable to cascading impacts and highlights advances in analyzing how these systems will interact with and respond to a changing environment (see Box 1.3).

Integrating Economics: This report, to a much greater degree than previous National Climate Assessments, includes broader and more systematic quantification of climate change impacts in economic terms. While this is an emerging body of literature that is not yet reflected in each of the 10 NCA regions, it represents a valuable advancement in our understanding of the financial costs and benefits of climate change impacts. Figure 1.21 provides an illustration of the type of economic information that is integrated throughout this report. It shows the financial damages *avoided* under a lower scenario (RCP4.5) versus a higher scenario (RCP8.5).

New Economic Impact Studies

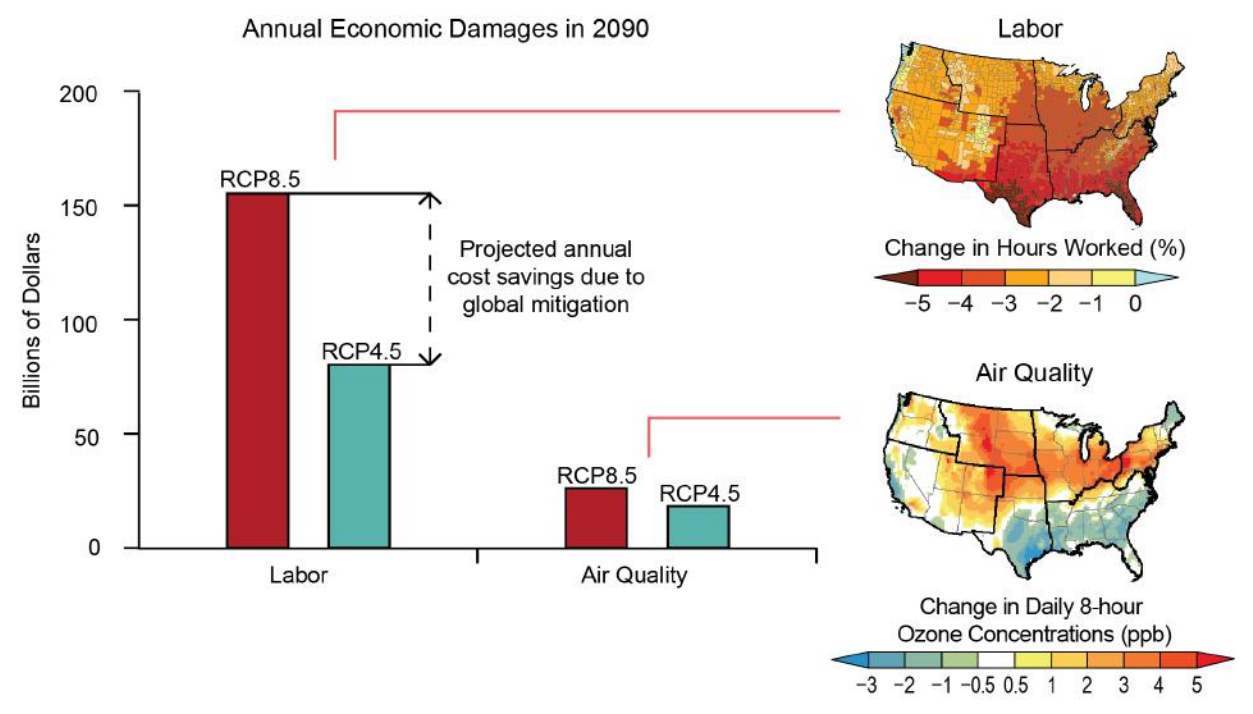


Figure 1.21: Annual economic impact estimates are shown for labor and air quality. The bar graph on the left shows national annual damages in 2090 (in billions of 2015 dollars) for a higher scenario (RCP8.5) and lower scenario (RCP4.5); the difference between the height of the RCP8.5 and RCP4.5 bars for a given category represents an estimate of the economic benefit to the United States from global mitigation action. For these two categories, damage estimates do not consider costs or benefits of new adaptation actions to reduce impacts, and they do not include Alaska, Hawai'i and U.S.-Affiliated Pacific Islands, or the U.S. Caribbean. The maps on the right show regional variation in annual impacts projected under the higher scenario (RCP8.5) in 2090. The map on the top shows the percent change in hours worked in high-risk industries as compared to the period 2003–2007. The hours lost result in economic damages: for example, $28 billion per year in the Southern Great Plains. The map on the bottom is the change in summer-average maximum daily 8-hour ozone concentrations (ppb) at ground-level as compared to the period 1995–2005. These changes in ozone concentrations result in premature deaths: for example, an additional 910 premature deaths each year in the Midwest. *Source: EPA, 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001.*

2 Our Changing Climate

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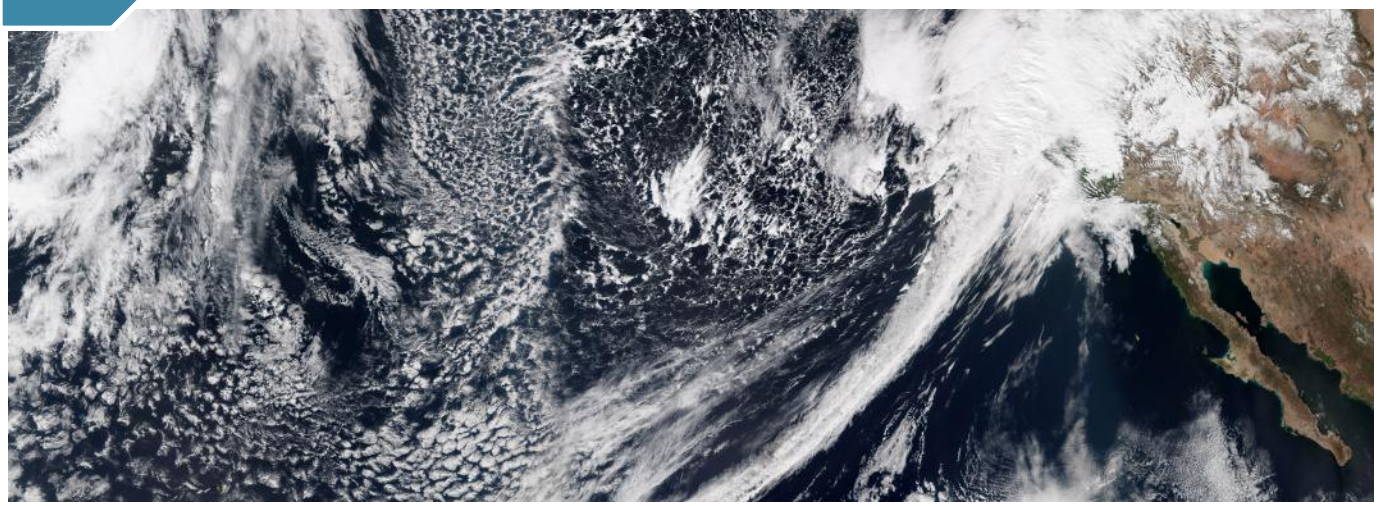
2 Our Changing Climate



An atmospheric river pours moisture into the western United States in February 2017.

Key Message 1

Observed Changes in Global Climate

Global climate is changing rapidly compared to the pace of natural variations in climate that have occurred throughout Earth's history. Global average temperature has increased by about 1.8°F from 1901 to 2016, and observational evidence does not support any credible natural explanations for this amount of warming; instead, the evidence consistently points to human activities, especially emissions of greenhouse or heat-trapping gases, as the dominant cause.

Key Message 2

Future Changes in Global Climate

Earth's climate will continue to change over this century and beyond. Past mid-century, how much the climate changes will depend primarily on global emissions of greenhouse gases and on the response of Earth's climate system to human-induced warming. With significant reductions in emissions, global temperature increase could be limited to 3.6°F (2°C) or less compared to preindustrial temperatures. Without significant reductions, annual average global temperatures could increase by 9°F (5°C) or more by the end of this century compared to preindustrial temperatures.

Key Message 3

Warming and Acidifying Oceans

The world's oceans have absorbed 93% of the excess heat from human-induced warming since the mid-20th century and are currently absorbing more than a quarter of the carbon dioxide emitted to the atmosphere annually from human activities, making the oceans warmer and more acidic. Increasing sea surface temperatures, rising sea levels, and changing patterns of precipitation, winds, nutrients, and ocean circulation are contributing to overall declining oxygen concentrations in many locations.

Key Message 4

Rising Global Sea Levels

Global average sea level has risen by about 7–8 inches (about 16–21 cm) since 1900, with almost half this rise occurring since 1993 as oceans have warmed and land-based ice has melted. Relative to the year 2000, sea level is very likely to rise 1 to 4 feet (0.3 to 1.3 m) by the end of the century. Emerging science regarding Antarctic ice sheet stability suggests that, for higher scenarios, a rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed.

Key Message 5

Increasing U.S. Temperatures

Annual average temperature over the contiguous United States has increased by 1.2°F (0.7°C) over the last few decades and by 1.8°F (1°C) relative to the beginning of the last century. Additional increases in annual average temperature of about 2.5°F (1.4°C) are expected over the next few decades regardless of future emissions, and increases ranging from 3°F to 12°F (1.6°–6.6°C) are expected by the end of century, depending on whether the world follows a higher or lower future scenario, with proportionally greater changes in high temperature extremes.

Key Message 6

Changing U.S. Precipitation

Annual precipitation since the beginning of the last century has increased across most of the northern and eastern United States and decreased across much of the southern and western United States. Over the coming century, significant increases are projected in winter and spring over the Northern Great Plains, the Upper Midwest, and the Northeast. Observed increases in the frequency and intensity of heavy precipitation events in most parts of the United States are projected to continue. Surface soil moisture over most of the United States is likely to decrease, accompanied by large declines in snowpack in the western United States and shifts to more winter precipitation falling as rain rather than snow.

Key Message 7

Rapid Arctic Change

In the Arctic, annual average temperatures have increased more than twice as fast as the global average, accompanied by thawing permafrost and loss of sea ice and glacier mass. Arctic-wide glacial and sea ice loss is expected to continue; by mid-century, it is very likely that the Arctic will be nearly free of sea ice in late summer. Permafrost is expected to continue to thaw over the coming century as well, and the carbon dioxide and methane released from thawing permafrost has the potential to amplify human-induced warming, possibly significantly.

Key Message 8

Changes in Severe Storms

Human-induced change is affecting atmospheric dynamics and contributing to the poleward expansion of the tropics and the northward shift in Northern Hemisphere winter storm tracks since 1950. Increases in greenhouse gases and decreases in air pollution have contributed to increases in Atlantic hurricane activity since 1970. In the future, Atlantic and eastern North Pacific hurricane rainfall and intensity are projected to increase, as are the frequency and severity of landfalling “atmospheric rivers” on the West Coast.

Key Message 9

Increases in Coastal Flooding

Regional changes in sea level rise and coastal flooding are not evenly distributed across the United States; ocean circulation changes, sinking land, and Antarctic ice melt will result in greater-than-average sea level rise for the Northeast and western Gulf of Mexico under lower scenarios and most of the U.S. coastline other than Alaska under higher scenarios. Since the 1960s, sea level rise has already increased the frequency of high tide flooding by a factor of 5 to 10 for several U.S. coastal communities. The frequency, depth, and extent of tidal flooding are expected to continue to increase in the future, as is the more severe flooding associated with coastal storms, such as hurricanes and nor'easters.

Key Message 10

Long-Term Changes

The climate change resulting from human-caused emissions of carbon dioxide will persist for decades to millennia. Self-reinforcing cycles within the climate system have the potential to accelerate human-induced change and even shift Earth's climate system into new states that are very different from those experienced in the recent past. Future changes outside the range projected by climate models cannot be ruled out, and due to their systematic tendency to underestimate temperature change during past warm periods, models may be more likely to underestimate than to overestimate long-term future change.

This chapter is based on the *Climate Science Special Report* (CSSR), which is Volume I of the Fourth National Climate Assessment (available at science2017.globalchange.gov). The Key Messages and the majority of the content represent the highlights of CSSR, updated with recent references relevant to these topics. The interested reader is referred to the relevant chapter(s) in CSSR for more detail on each of the Key Messages that follow.

Key Message 1

Observed Changes in Global Climate

Global climate is changing rapidly compared to the pace of natural variations in climate that have occurred throughout Earth's history. Global average temperature has increased by about 1.7°F from 1901 to 2016, and observational evidence does not support any credible natural explanations for this amount of warming; instead, the evidence consistently points to human activities, especially emissions of greenhouse or heat-trapping gases, as the dominant cause.

Long-term temperature observations are among the most consistent and widespread evidence of a warming planet. Global annually averaged temperature measured over both land and oceans has increased by about 1.8°F (1.0°C) according to a linear trend from 1901 to 2016, and by 1.2°F (0.65°C) for the period 1986–2015 as compared to 1901–1960. The last few years have also seen record-breaking, climate-related weather extremes. For example, since the Third National Climate Assessment was published,[1] 2014 became the warmest year on record globally; 2015 surpassed 2014 by a wide margin; and 2016 surpassed 2015.[2,3] Sixteen of the last 17 years have been the warmest ever recorded by human observations.

For short periods of time, from a few years to a decade or so, the increase in global temperature can be temporarily slowed or even reversed by natural variability (see Box 2.1). Over the past decade, such a slowdown led to numerous assertions that global warming had stopped. No temperature records, however, show that long-term global warming has ceased or even substantially slowed over the past decade.[4,5,6,7,8,9] Instead, global annual average temperatures for the period since 1986 are likely much higher and appear to have risen at a more rapid rate than for any similar climatological (20–30 year) time period in at least the last 1,700 years.[10,11]

While thousands of studies conducted by researchers around the world have documented increases in temperature at Earth's surface, as well as in the atmosphere and oceans, many other aspects of global climate are also changing[12,13] (see also EPA 2016, Wuebbles et al. 2017[10,14]). Studies have documented melting glaciers and ice sheets, shrinking snow cover and sea ice, rising sea levels, more frequent high temperature extremes and heavy precipitation events, and a host of other climate variables or "indicators" consistent with a warmer world (see Box 2.2). Observed trends have been confirmed by multiple independent research groups around the world.

Many lines of evidence demonstrate that human activities, especially emissions of greenhouse gases from fossil fuel combustion, deforestation, and land-use change, are primarily responsible for the climate changes observed in the industrial era, especially over the last six decades. Observed warming over the period 1951–2010 was 1.2°F (0.65°C), and formal detection and attribution studies conclude that the *likely* range of the human contribution to the global average temperature increase over the period 1951–2010 is 1.1°F to 1.4°F (0.6°C to 0.8°C;[15] see Knutson et al. 2017[16] for more on detection and attribution).

Human activities affect Earth's climate by altering factors that control the amount of energy from the sun that enters and leaves the atmosphere. These factors, known as radiative forcings, include changes in greenhouse gases, small airborne soot and dust particles known as aerosols, and the reflectivity (or albedo) of Earth's surface through land-use and land-cover changes (see Ch. 5: Land Changes).[17,18] Increasing greenhouse gas levels in the atmosphere due to emissions from human activities are the largest of these radiative forcings. By absorbing the heat emitted by Earth and reradiating it equally in all directions, greenhouse gases increase the amount of heat retained inside the climate system, warming the planet. Aerosols produced by burning fossil fuels and by other human activities affect climate both directly, by scattering and absorbing sunlight, as well as indirectly, through their impact on cloud formation and cloud properties. Over the industrial era, the net effect of the combined direct and indirect effects of aerosols has been to cool the planet, partially offsetting greenhouse gas warming at the global scale.[17,18]

Box 2.1: Natural Variability

The conditions we experience in a given place at a given time are the result of both human and natural factors.

Long-term trends and future projections describe changes to the average state of the climate. The actual weather experienced is the result of combining long-term human-induced change with natural factors and the hard-to-predict variations of the weather in a given place, at a given time. Temperature, precipitation, and other day-to-day weather conditions are influenced by a range of factors, from fixed local conditions (such as topography and urban heat islands) to the cyclical and chaotic patterns of natural variability within the climate system, like El Niño. Over shorter timescales and smaller geographic regions, the influence of natural variability can be larger than the influence of human activity.[10] Over longer timescales and larger geographic regions, however, the human influence can dominate. For example, during an El Niño year, winters across the southwestern United States are typically wetter than average, and global temperatures are higher than average. During a La Niña year, conditions across the southwestern United States are typically dry, and global temperatures tend to be cooler. Over climate timescales of multiple decades, however, global temperature continues to steadily increase.

How will global climate—and even more importantly, regional climate—change over the next few decades? The actual state of the climate depends on both natural variability and human-induced change. At the decadal scale, these two factors are equally strong.[202] Scientific ability to predict the climate at the seasonal to decadal scale is limited both by the imperfect ability to specify the initial conditions of the state of the ocean (such as surface temperature and salinity) and the chaotic nature of the interconnected earth system.[203,204] Over longer time scales (about 30 years, for global climate indicators; see Box 2.2), the human influence dominates.[205] As human forcing exceeds the influence of natural variability for many aspects of Earth's climate system, uncertainty in human choices and resulting emissions becomes increasingly important in determining the magnitude and patterns of future global warming. Natural variability will continue to be a factor, but most of the differences between present and future climates will be determined by choices that society makes today and over the next few decades that determine emissions of carbon dioxide and other heat-trapping gases, as well as any potential large-scale interventions as discussed in DeAngelo et al. (2017).[27] The further out in time we look, the greater the influence of these human choices on the magnitude of future warming.

Box 2.2: Indicators

Observed trends in a broad range of physical climate indicators show that Earth is warming.

There are many different types of physical observations, or "indicators," that can be used to track how climate is changing (see Ch. 1: Overview, Figure 1.2). These indicators include changes in temperature and precipitation as well as observations of arctic sea ice, snow cover, alpine glaciers, growing season length, drought, wildfires, lake levels, and heavy precipitation. Some of these indicators, especially those derived from air temperature and precipitation observations, have nearly continuous data that extend back to the late 1800s in the United States (Blue Hill Meteorological Observatory)[206] and the 1600s in Europe (Central England Temperature Record).[207] These document century-scale changes in climate. Satellite-based indicators, on the other hand, extend back only to the late 1970s but provide an unparalleled and comprehensive record of the changes in Earth's surface and atmosphere. Various chapters in CSSR discuss the different types of observations that capture the interconnected nature of the climate system.

Taken individually, each indicator simply shows changes that are occurring in that variable. Taken as a whole, however, in the context of scientific understanding of the climate system, the cumulative changes documented by each of these indicators paint a compelling and consistent picture of a warming world. For example, arctic sea ice has declined since the late 1970s, most glaciers have retreated, the frost-free season has lengthened, heavy precipitation events have increased in the United States and elsewhere in the world, and sea level has risen. Each of these indicators, and many more, are changing in ways that are consistent with a warming climate.

The U.S. Global Change Research Program (USGCRP) and the Environmental Protection Agency (EPA) maintain websites that document many of these kinds of indicators (see http://www.globalchange.gov/browse/indicators and https://www.epa.gov/climate-indicators).

Over the last century, changes in solar output, volcanic emissions, and natural variability have only contributed marginally to the observed changes in climate (Figure 2.1).[15,17] No natural cycles are found in the observational record that can explain the observed increases in the heat content of the atmosphere, the ocean, or the cryosphere since the industrial era.[11,19,20,21] Greenhouse gas emissions from human activities are the only factors that can account for the observed warming over the last century; there are no credible alternative human or natural explanations supported by the observational evidence.[10,22]

Human and Natural Influences on Global Temperature

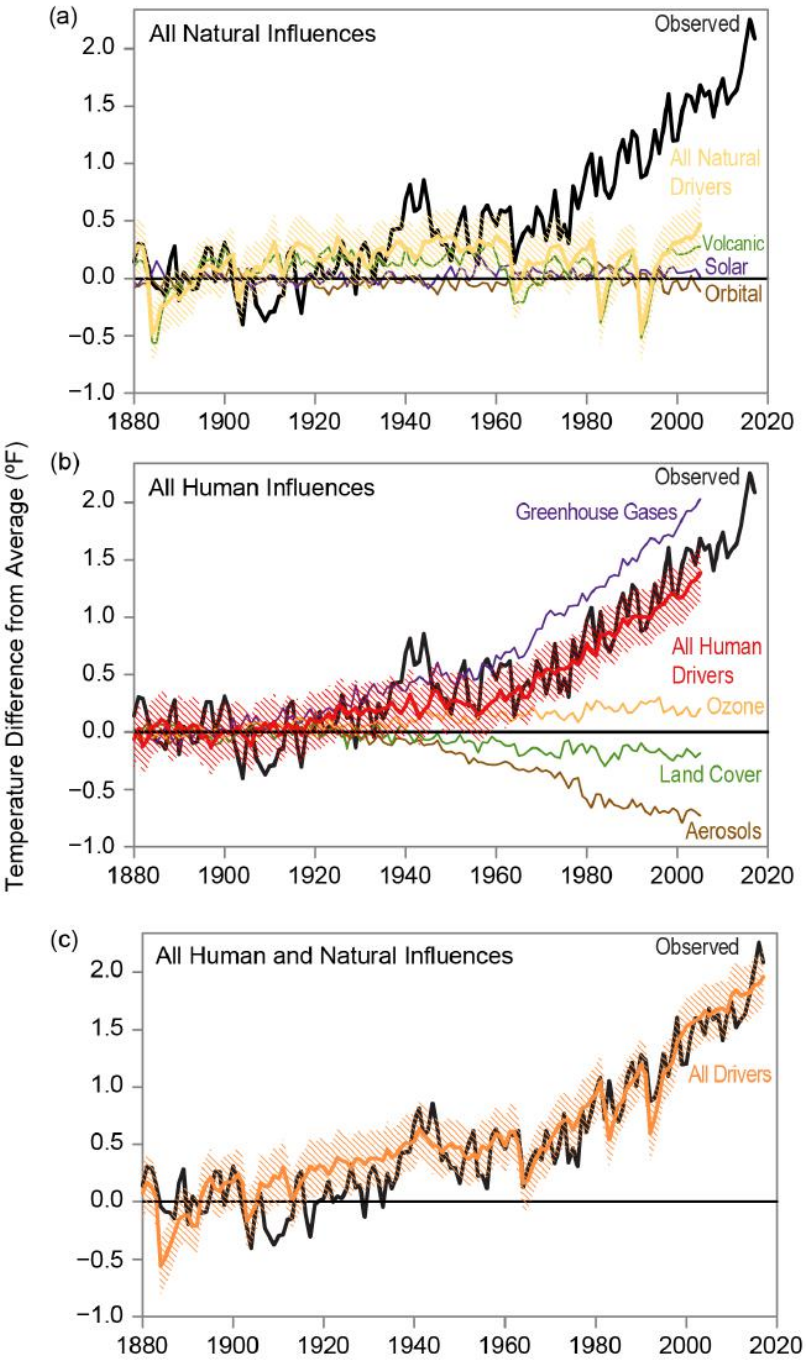


Figure 2.1: Both human and natural factors influence Earth's climate, but the long-term global warming trend observed over the past century can only be explained by the effect that human activities have had on the climate.

Sophisticated computer models of Earth's climate system allow scientists to explore the effects of both natural and human factors. In all three panels of this figure, the black line shows the observed annual average global surface temperature for 1880–2017 as a difference from the average value for 1880–1910.

The top panel (a) shows the temperature changes simulated by a climate model when only natural factors (yellow line) are considered. The other lines show the individual contributions to the overall effect from observed changes in Earth's orbit (brown line), the amount of incoming energy from the sun (purple line), and changes in emissions from volcanic eruptions (green line). Note that no long-term trend in globally averaged surface temperature over this time period would be expected from natural factors alone.[10]

The middle panel (b) shows the simulated changes in global temperature when considering only human influences (dark red line), including the contributions from emissions of greenhouse gases (purple line) and small particles (referred to as aerosols, brown line) as well as changes in ozone levels (orange line) and changes in land cover, including deforestation (green line). Changes in aerosols and land cover have had a net cooling effect in recent decades, while changes in near-surface ozone levels have had a small warming effect.[18] These smaller effects are dominated by the large warming influence of greenhouse gases such as carbon dioxide and methane. Note that the net effect of human factors (dark red line) explains most of the long-term warming trend.

The bottom panel (c) shows the temperature change (orange line) simulated by a climate model when both human and natural influences are included. The result matches the observed temperature record closely, particularly since 1950, making the dominant role of human drivers plainly visible.

Researchers do not expect climate models to exactly reproduce the specific timing of actual weather events or short-term climate variations, but they do expect the models to capture how the whole climate system behaves over long periods of time. The simulated temperature lines represent the average values from a large number of simulation runs. The orange hatching represents uncertainty bands based on those simulations. For any given year, 95% of the simulations will lie inside the orange bands. Source: NASA GISS.

Key Message 2

Future Changes in Global Climate

Earth's climate will continue to change over this century and beyond. Past mid-century, how much the climate changes will depend primarily on global emissions of greenhouse gases and on the response of Earth's climate system to human-induced warming. With significant reductions in emissions, global temperature increase could be limited to 3.6°F (2°C) or less compared to preindustrial temperatures. Without significant reductions, annual average global temperatures could increase by 9°F (5°C) or more by the end of this century compared to preindustrial temperatures.

Beyond the next few decades, how much the climate changes will depend primarily on the amount of greenhouse gases emitted into the atmosphere; how much of those greenhouse gases are absorbed by the ocean, the biosphere, and other sinks; and how sensitive Earth's climate is to those emissions.[23] Climate sensitivity is typically defined as the long-term change that would result from a doubling of carbon dioxide in the atmosphere relative to preindustrial levels; its exact value is uncertain due to the interconnected nature of the land–atmosphere–ocean system. Changes in one aspect of the system can lead to self-reinforcing cycles that can either amplify or weaken the climate system's responses to human and natural influences, creating a positive feedback or self-reinforcing cycle in the first case and a negative feedback in the second.[18] These feedbacks operate on a range of timescales from very short (essentially instantaneous) to very long (centuries). While there are uncertainties associated with modeling some of these feedbacks,[24,25] the most up-to-date scientific assessment shows that the net effect of these feedbacks over the industrial era has been to amplify human-induced warming, and this amplification will continue over coming decades[18] (see Box 2.3).

Because it takes some time for Earth's climate system to fully respond to an increase in greenhouse gas concentrations, even if these concentrations could be stabilized at their current level in the atmosphere, the amount that is already there is projected to result in at least an additional 1.1°F (0.6°C) of warming over this century relative to the last few decades.[24,26] If emissions continue, projected changes in global average temperature corresponding to the scenarios used in this assessment (see Box 2.4) range from 4.2°–8.5°F (2.4°–4.7°C) under a higher scenario (RCP8.5) to 0.4°–2.7°F (0.2°–1.5°C) under a very low scenario (RCP2.6) for the period 2080–2099 relative to 1986–2015 (Figure 2.2).[24] However, these scenarios do not encompass all possible futures. With significant reductions in emissions of greenhouse gases, the future rise in global average temperature could be limited to 3.6°F (2°C) or less, consistent with the aim of the Paris Agreement (see Box 2.4).[27] Similarly, without major reductions in these emissions, the increase in annual average global temperatures relative to preindustrial times could reach 9°F (5°C) or more by the end of this century.[24] Because of the slow timescale over which the ocean absorbs heat, warming that results from emissions that occur during this century will leave a multi-millennial legacy, with a substantial fraction of the warming persisting for more than 10,000 years.[28,29,30]

Box 2.3: The Climate Science Special Report (CSSR), NCA4 Volume I

This chapter highlights key findings from the *Climate Science Special Report* (2017).

Periodically taking stock of the current state of knowledge about climate change and putting new weather extremes, changes in sea ice, increases in ocean temperatures, and ocean acidification into context ensures that rigorous, scientific-based information is available to inform dialog and decisions at every level. This is the purpose of the USGCRP's *Climate Science Special Report* (CSSR),[208] which is Volume I of the Fourth National Climate Assessment (NCA4), as required by the U.S. Global Change Research Act of 1990. CSSR updates scientific understanding of past, current, and future climate change with the observations and research that have emerged since the Third National Climate Assessment (NCA3) was published in May 2014. It discusses climate trends and findings at the global scale, then focuses on specific areas, from observed and projected changes in temperature and precipitation to the importance of human choice in determining our climate future.

Since NCA3, stronger evidence has emerged for continuing, rapid, human-caused warming of the global atmosphere and ocean. The CSSR definitively concludes that, "human activities, especially emissions of greenhouse gases, are the dominant cause of the observed climate changes in the industrial era, especially over the last six decades. Over the last century, there are no credible alternative explanations supported by the full extent of the observational evidence."

Since 1980, the number of extreme weather-related events per year costing the American people more than one billion dollars per event has increased significantly (accounting for inflation), and the total cost of these extreme events for the United States has exceeded $1.1 trillion. Improved understanding of the frequency and severity of these events in the context of a changing climate is critical.

The last few years have also seen record-breaking, climate-related weather extremes, the three warmest years on record for the globe, and continued decline in arctic sea ice. These types of records are expected to continue to be broken in the future. Significant advances have also been made in the understanding of observed individual extreme weather events, such as the 2011 hot summer in Texas and Oklahoma,[209,210,211] the recent California agricultural drought,[212,213] the spring 2013 wet season in the Upper Midwest,[214,215] and most recently Hurricane Harvey (see Box 2.5),[216,217,218] and how they relate to increasing global temperatures and associated climate changes. This chapter presents the highlights from CSSR. More examples are provided in Vose et al. (2017),[85] Table 6.3; Easterling et al. (2017),[94] Table 7.1; and Wehner et al. (2017),[101] Table 8.1; and additional details on what is new since NCA3 can be found in Fahey et al. (2017),[18] Box 2.3.

Observed and Projected Changes in Carbon Emissions and Temperature

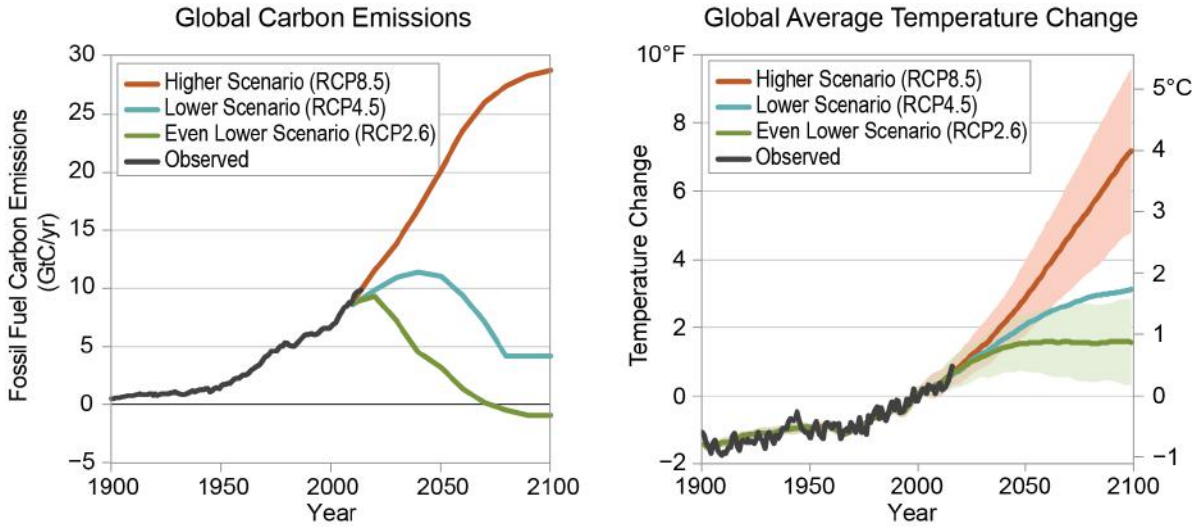


Figure 2.2: Observed and projected changes in global average temperature (right) depend on observed and projected emissions of carbon dioxide from fossil fuel combustion (left) and emissions of carbon dioxide and other heat-trapping gases from other human activities, including land use and land-use change. Under a pathway consistent with a higher scenario (RCP8.5), fossil fuel carbon emissions continue to increase throughout the century, and by 2080–2099, global average temperature is projected to increase by 4.2°–8.5°F (2.4°–4.7°C; shown by the burnt orange shaded area) relative to the 1986–2015 average. Under a lower scenario (RCP4.5), fossil fuel carbon emissions peak mid-century then decrease, and global average temperature is projected to increase by 1.7°–4.4°F (0.9°–2.4°C; range not shown on graph) relative to 1986–2015. Under an even lower scenario (RCP2.6), assuming carbon emissions from fossil fuels have already peaked, temperature increases could be limited to 0.4°–2.7°F (0.2°–1.5°C; shown by green shaded area) relative to 1986–2015. Thick lines within shaded areas represent the average of multiple climate models. The shaded ranges illustrate the 5% to 95% confidence intervals for the respective projections. In all RCP scenarios, carbon emissions from land use and land-use change amount to less than 1 GtC by 2020 and fall thereafter. Limiting the rise in global average temperature to less than 2.2°F (1.2°C) relative to 1986–2015 is approximately equivalent to 3.6°F (2°C) or less relative to preindustrial temperatures, consistent with the aim of the Paris Agreement (see Box 2.4). Source: adapted from Wuebbles et al. 2017.[10]

Box 2.4: Cumulative Carbon and 1.5°/2°C Targets

Limiting global average temperature increase to 3.6°F (2°C) will require a major reduction in emissions.

Projections of future changes in climate are based on scenarios of greenhouse gas emissions and other pollutants from human activities. The primary scenarios used in this assessment are called Representative Concentration Pathways (RCPs)[219] and are numbered according to changes in radiative forcing (a measure of the influence that a factor, such as greenhouse gas emissions, has in changing the global balance of incoming and outgoing energy) in 2100 relative to preindustrial conditions: +2.6 (very low), +4.5 (lower), +6.0 (mid-high) and +8.5 (higher) watts per square meter (W/m^2). Some scenarios are consistent with increasing dependence on fossil fuels, while others could only be achieved by deliberate actions to reduce emissions (see Section 4.2 in Hayhoe et al. 2017[24] for more details). The resulting range in forcing scenarios reflects the uncertainty inherent in quantifying human activities and their influence on climate (e.g., Hawkins and Sutton 2009, 2011[23,220]).

Which scenario is more likely? The observed acceleration in carbon emissions over the past 15–20 years has been consistent with the higher future scenarios (such as RCP8.5) considered in this assessment.[221,222,223] Since 2014, however, the growth in emission rates of carbon dioxide has begun to slow as economic growth has become less carbon-intensive[224,225,226] with the trend in 2016 estimated at near zero.[227,228] Preliminary data for 2017, however, indicate growth in carbon emissions once again.[228] These latest results highlight how separating systemic change due to decarbonization from short-term variability that is often affected by economic changes remains difficult.

Box 2.4: Cumulative Carbon and 1.5°/2°C Targets, *continued*

To stabilize the global temperature at any level requires that emission rates decrease eventually to zero. To stabilize global average temperature at or below specific long-term warming targets such as 3.6°F (2°C), or the more ambitious target of 2.7°F (1.5°C), would require substantial reductions in net global carbon emissions relative to present-day values well before 2040, and likely would require net emissions to become zero or possibly negative later in the century. Accounting for emissions of carbon as well as other greenhouse gases and particles that remain in the atmosphere from weeks to centuries, cumulative human-caused carbon emissions since the beginning of the industrial era would likely need to stay below about 800 GtC in order to provide a two-thirds likelihood of preventing 3.6°F (2°C) of warming, implying that approximately only 230 GtC more could be emitted globally in order to meet that target.[27] Several recent studies specifically examine remaining emissions commensurate with 3.6°F (2°C) warming. They show estimates of cumulative emissions that are both smaller and larger due to a range of factors and differences in underlying assumptions (e.g., Millar et al. 2017 and correction, Rogelj et al. 2018[229,230,231]).

If global emissions are consistent with a pathway that lies between the higher RCP8.5 and lower RCP4.5 scenarios, emissions could continue for only about two decades before this cumulative carbon threshold is exceeded. Any further emissions beyond these thresholds would cause global average temperature to overshoot the 2°C warming target. At current emission rates, unless there is a very rapid decarbonization of the world's energy systems over the next few decades, stabilization at neither target would be remotely possible.[27,229,232,233]

In addition, the warming and associated climate effects from carbon emissions will persist for decades to millennia.[234,235] Climate intervention or geoengineering strategies, such as solar radiation management, are measures that attempt to limit the increase in or reduce global temperature. For many of these proposed strategies, however, the technical feasibilities, costs, risks, co-benefits, and governance challenges remain unproven. It would be necessary to comprehensively assess these strategies before their benefits and risks can be confidently judged.[27]

Key Message 3

Warming and Acidifying Oceans

The world's oceans have absorbed 93% of the excess heat from human-induced warming since the mid-20th century and are currently absorbing more than a quarter of the carbon dioxide emitted to the atmosphere annually from human activities, making the oceans warmer and more acidic. Increasing sea surface temperatures, rising sea levels, and changing patterns of precipitation, winds, nutrients, and ocean circulation are contributing to overall declining oxygen concentrations in many locations.

Oceans occupy over 70% of the planet's surface and host unique ecosystems and species, including those important for global commercial and subsistence fishing. For this reason, it is essential to highlight the fact that observed changes in the global average temperature of the atmosphere represent only a small fraction of total warming. Since the 1950s, the oceans have absorbed 93% of the excess heat in the earth system that has built up as a result of increasing concentrations of greenhouse gases in the atmosphere.[31,32] Significant increases in heat content have been observed over the upper 6,560 feet (2,000 m) of the ocean since the 1960s, with surface oceans warming by about 1.3° ± 0.1°F (0.7° ± 0.1°C) globally from 1900 to 2016.[20,31,33,34]

Oceans' net uptake of CO_2 each year is approximately equal to a quarter of that emitted to the atmosphere annually from human activities.[35,36] It is primarily controlled by the difference between CO_2 concentrations in the atmosphere and ocean, with small variations from year to year due to changes in ocean circulation and biology. This carbon uptake is making near-surface ocean waters more acidic, which in turn can harm vulnerable marine ecosystems (see Ch. 9: Oceans; Ch. 26: Alaska; Ch. 27: Hawai'i & Pacific Islands). Although tropical coral reefs are the most frequently cited casualties of ocean warming and acidification, ecosystems at higher latitudes can be more vulnerable than those at lower latitudes as they typically have a lower buffering capacity against changing acidity. Regionally, acidification is greater along the U.S. coast than the global average, as a result of upwelling (for example, in the Pacific Northwest), changes in freshwater inputs (such as in the Gulf of Maine), and nutrient input (as in urbanized estuaries).[34,37,38,39,40,41,42]

In addition to higher temperatures and increasing acidification, ocean oxygen levels are also declining in various ocean locations and in many coastal areas.[43,44] This decline is due to a combination of increasing sea surface temperatures (SSTs), rising sea levels inundating coastal wetlands, and changing patterns of precipitation, winds, nutrients, and ocean circulation. Over the last 50 years, declining oxygen levels have been observed in many inland seas, estuaries, and nearshore coastal waters.[43,45,46,47,48,49,50,51,52] This is a concern because oxygen is essential to most life in the ocean, governing a host of biogeochemical and biological processes that ultimately shape the composition, diversity, abundance, and distribution of organisms from microbes to whales.[34]

By 2100, under a higher scenario (RCP8.5; see Box 2.4), average SST is projected to increase by 4.9° ± 1.3°F (2.7° ± 0.7°C) as compared to late 20th-century values, ocean oxygen levels are projected to decrease by 3.5%,[53] and global average surface ocean acidity is projected to increase by 100% to 150%.[32] This rate of acidification would be unparalleled in at least the past 66 million years.[34,54,55]

Key Message 4

Rising Global Sea Levels

Global average sea level has risen by about 7–8 inches (about 16–21 cm) since 1900, with almost half this rise occurring since 1993 as oceans have warmed and land-based ice has melted. Relative to the year 2000, sea level is very likely to rise 1 to 4 feet (0.3 to 1.3 m) by the end of the century. Emerging science regarding Antarctic ice sheet stability suggests that, for higher scenarios, a rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed.

Global sea level is rising due to two primary factors. First, as the ocean warms (see Key Message 3), seawater expands, increasing the overall volume of the ocean—a process known as thermal expansion. Second, the amount of seawater in the ocean is increasing as land-based ice from mountain glaciers and the Antarctic and Greenland ice sheets melts and runs off into the ocean.[56,57] Over the last century, about one-third of global average sea level rise has come from thermal expansion and the remainder from melting of land-based ice, with human-caused warming making a substantial contribution to the overall amount of rise.[58,59,60,61,62,63] To a much lesser degree, global average sea level is also affected by changes in the amount of water stored on land, including in soil, lakes, reservoirs, and aquifers.[56,64,65,66,67]

Since 1900, global average sea level has risen by about 7–8 inches (about 16–21 cm). The rate of sea level rise over the 20th century was higher than in any other century in at least the last 2,800 years, according to proxy data such as salt marsh sediments and fossil corals.[58] Since the early 1990s, the rate of global average sea level rise has increased due to increased melting of land-based ice.[56,68,69,70,71,72] As a result, almost half (about 0.12 inches [3 mm] per year) of the observed rise of 7–8 inches (16–21 cm) has occurred since 1993.[73,74,75]

Over the first half of this century, the future scenario the world follows has little effect on projected sea level rise due to the inertia in the climate system. However, the magnitude of human-caused emissions this century significantly affects projections for the second half of the century and beyond (Figure 2.3). Relative to the year 2000, global average sea level is very likely to rise by 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1–4 feet (30–130 cm) by 2100.[56,57,58,59,76,77,78,79] These estimates are generally consistent with the assumption—possibly flawed—that the relationship between global temperature and global average sea level in the coming century will be similar to that observed over the last two millennia.[58] These ranges do not, however, capture the full range of physically plausible global average sea level rise over the 21st century. Several avenues of research, including emerging science on physical feedbacks in the Antarctic ice sheet (e.g., DeConto and Pollard 2016, Kopp et al. 2017[80,81]) suggest that global average sea level rise exceeding 8 feet (2.5 m) by 2100 is physically plausible, although its probability cannot currently be assessed (see Sweet et al. 2017, Kopp et al. 2017[57,25]).

Regardless of future scenario, it is extremely likely that global average sea level will continue to rise beyond 2100.[82] Paleo sea level records

Historical and Projected Global Average Sea Level Rise

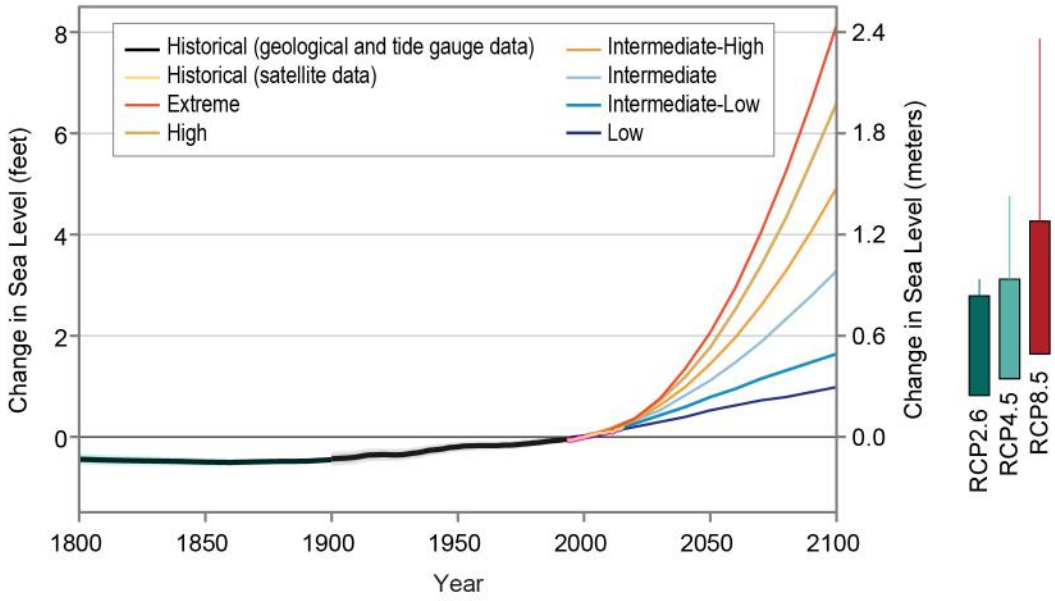


Figure 2.3. How much global average sea level will rise over the rest of this century depends on the response of the climate system to warming, as well as on future scenarios of human-caused emissions of heat-trapping gases. The colored lines show the six different global average sea level rise scenarios, relative to the year 2000, that were developed by the U.S. Federal Interagency Sea Level Rise Taskforce[76] to describe the range of future possible rise this century. The boxes on the right-hand side show the *very likely* ranges in sea level rise by 2100, relative to 2000, corresponding to the different RCP scenarios described in Figure 2.2. The lines above the boxes show possible increases based on the newest research of the potential Antarctic contribution to sea level rise (for example, DeConto and Pollard 2016[80] versus Kopp et al. 2014[77]). Regardless of the scenario followed, it is *extremely likely* that global average sea level rise will continue beyond 2100. Source: adapted from Sweet et al. 2017.[57]

suggest that 1.8°F (1°C) of warming may already represent a long-term commitment to more than 20 feet (6 meters) of global average sea level rise;[83,84] a 3.6°F (2°C) warming represents a 10,000-year commitment to about 80 feet (25 m), and 21st-century emissions consistent with the higher scenario (RCP8.5) represent a 10,000-year commitment to about 125 feet (38 m) of global average sea level rise.[30] Under 3.6°F (2°C), about one-third of the Antarctic ice sheet and three-fifths of the Greenland ice sheet would ultimately be lost, while under the RCP8.5 scenario, a complete loss of the Greenland ice sheet is projected over about 6,000 years.[30]

Key Message 5

Increasing U.S. Temperatures

Annual average temperature over the contiguous United States has increased by 1.2°F (0.7°C) over the last few decades and by 1.8°F (1°C) relative to the beginning of the last century. Additional increases in annual average temperature of about 2.5°F (1.4°C) are expected over the next few decades regardless of future emissions, and increases ranging from 3°F to 12°F (1.6°–6.6°C) are expected by the end of century, depending on whether the world follows a higher or lower future scenario, with proportionally greater changes in high temperature extremes.

Over the contiguous United States, annual average temperature has increased by 1.2°F (0.7°C) for the period 1986–2016 relative to 1901–1960, and by 1.8°F (1.0°C) when calculated using a linear trend for the entire period of record.[85] Surface and satellite data both show accelerated warming from 1979 to 2016, and paleoclimate records of temperatures over the United States show that recent decades are the warmest in at least the past 1,500 years.[86]

At the regional scale, each National Climate Assessment (NCA) region experienced an overall warming between 1901–1960 and 1986–2016 (Figure 2.4). The largest changes were in the western half of the United States, where average temperature increased by more than 1.5°F (0.8°C) in Alaska, the Northwest, the Southwest, and also in the Northern Great Plains. Over the entire period of record, the Southeast has had the least warming due to a combination of natural variations and human influences;[87] since the early 1960s, however, the Southeast has been warming at an accelerated rate.[88,89]

Over the past two decades, the number of high temperature records recorded in the United States far exceeds the number of low temperature records. The length of the frost-free season, from the last freeze in spring to the first freeze of autumn, has increased for all regions since the early 1900s.[85,90] The frequency of cold waves has decreased since the early 1900s, and the frequency of heat waves has increased since the mid-1960s. Over timescales shorter than a decade, the 1930s Dust Bowl remains the peak period for extreme heat in the United States for a variety of reasons, including exceptionally dry springs coupled with poor land management practices during that era.[85,91,92,93]

Over the next few decades, annual average temperature over the contiguous United States is projected to increase by about 2.2°F (1.2°C) relative to 1986–2015, regardless of future scenario. As a result, recent record-setting hot years are projected to become common in the near future for the United States. Much larger increases are projected by late century: 2.3°–6.7°F (1.3°–3.7°C) under a lower scenario (RCP4.5) and 5.4°–11.0°F (3.0°–6.1°C) under a higher scenario (RCP8.5) relative to 1986–2015 (Figure 2.4).[85]

Observed and Projected Changes in Annual Average Temperature

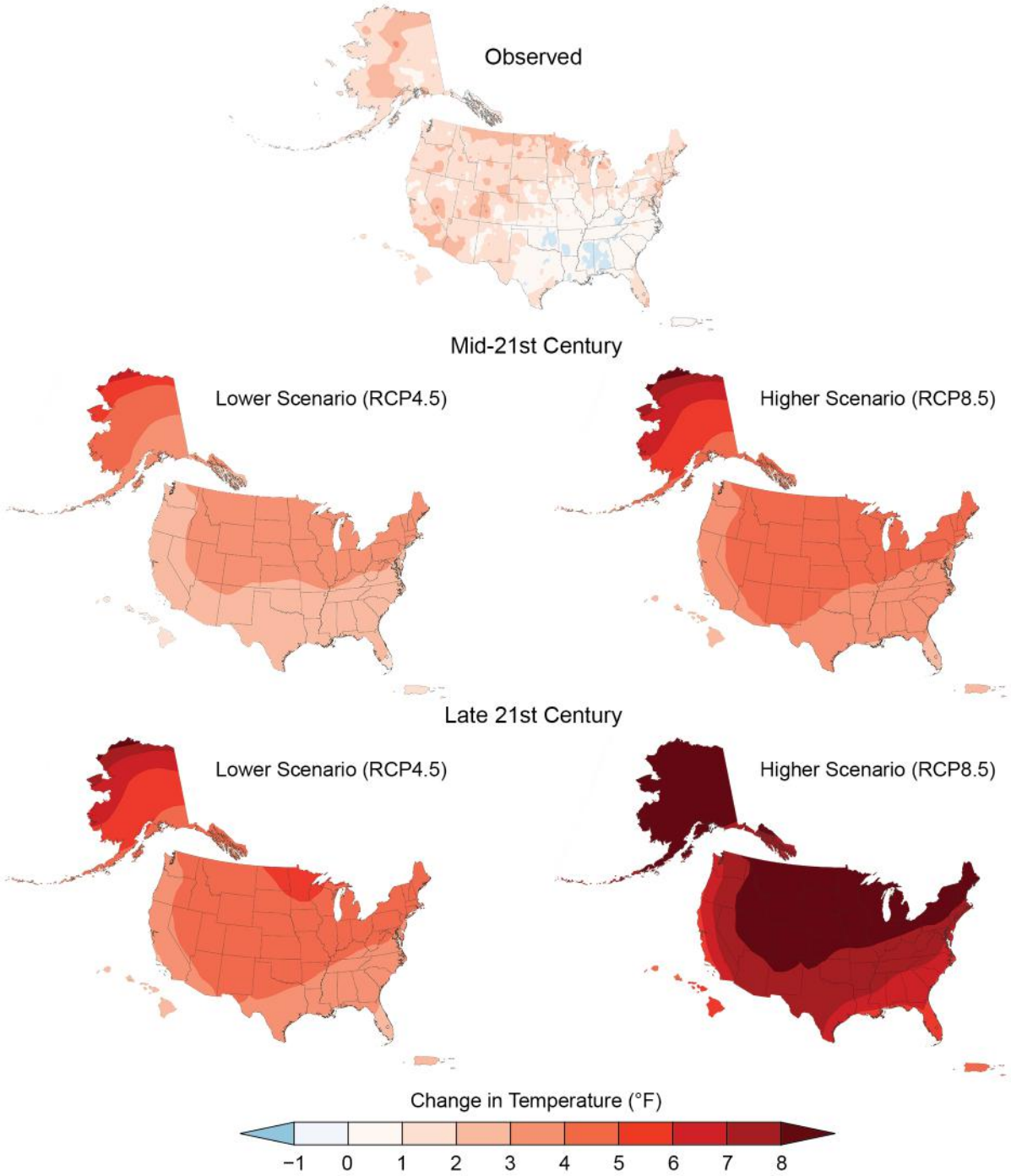


Figure 2.4: Annual average temperatures across North America are projected to increase, with proportionally greater changes at higher as compared to lower latitudes, and under a higher scenario (RCP8.5, right) as compared to a lower one (RCP4.5, left). This figure compares (top) observed change for 1986–2016 (relative to 1901–1960 for the contiguous United States and 1925–1960 for Alaska, Hawai'i, Puerto Rico, and the U.S. Virgin Islands) with projected differences in annual average temperature for mid-century (2036–2065, middle) and end-of-century (2070–2099, bottom) relative to the near-present (1986–2015). Source: adapted from Vose et al. 2017.[85]

Extreme high temperatures are projected to increase even more than average temperatures. Cold waves are projected to become less intense and heat waves more intense. The number of days below freezing is projected to decline, while the number of days above 90°F is projected to rise.[85]

Key Message 6

Changing U.S. Precipitation

Annual precipitation since the beginning of the last century has increased across most of the northern and eastern United States and decreased across much of the southern and western United States. Over the coming century, significant increases are projected in winter and spring over the Northern Great Plains, the Upper Midwest, and the Northeast. Observed increases in the frequency and intensity of heavy precipitation events in most parts of the United States are projected to continue. Surface soil moisture over most of the United States is likely to decrease, accompanied by large declines in snowpack in the western United States and shifts to more winter precipitation falling as rain rather than snow.

Annual average precipitation has increased by 4% since 1901 across the entire United States, with strong regional differences: increases over the Northeast, Midwest, and Great Plains and decreases over parts of the Southwest and Southeast (Figure 2.5),[94] consistent with the human-induced expansion of the tropics.[95] In the future, the greatest precipitation changes are projected to occur in winter and spring, with similar geographic patterns to observed changes: increases across the Northern Great Plains, the Midwest, and the Northeast and decreases in the Southwest (Figure 2.5, bottom). For 2070–2099 relative to 1986–2015, precipitation increases of up to 20% are projected in winter and spring for the north central United States and more than 30% in Alaska, while precipitation is projected to decrease by 20% or more in the Southwest in spring. In summer, a slight decrease is projected across the Great Plains, with little to no net change in fall.

The frequency and intensity of heavy precipitation events across the United States have increased more than average precipitation (Figure 2.6, top) and are expected to continue to increase over the coming century, with stronger trends under a higher as compared to a lower scenario (Figure 2.6).[94] Observed trends and model projections of increases in heavy precipitation are supported by well-established physical relationships between temperature and humidity (see Easterling et al. 2017,[94] Section 7.1.3 for more information). These trends are consistent with what would be expected in a warmer world, as increased evaporation rates lead to higher levels of water vapor in the atmosphere, which in turn lead to more frequent and intense precipitation extremes.

For heavy precipitation events above the 99th percentile of daily values, observed changes for the Northeast and Midwest average 38% and 39%, respectively, when measured from 1901, and 55% and 42%, respectively, when measured with the more robust network available from 1958. The largest observed increases have occurred and are projected to continue to occur in the Northeast and Midwest, where additional increases exceeding 40% are projected for these regions by 2070–2099 relative to 1986–2015. These increases are linked to observed and projected increases in the frequency of organized clusters of thunderstorms and the amount of precipitation associated with them.[96,97,98]

Observed and Projected Change in Seasonal Precipitation

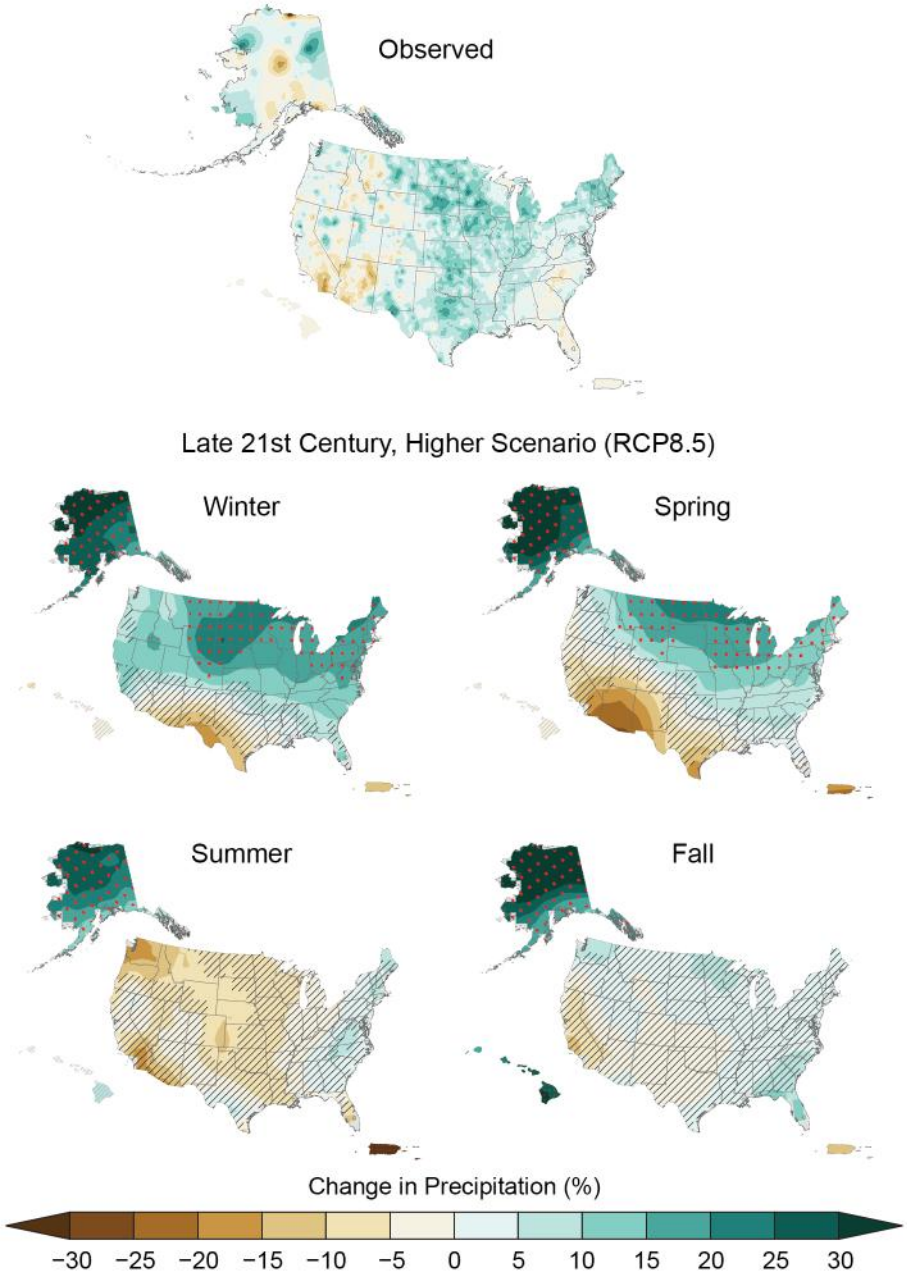


Figure 2.5: Observed and projected precipitation changes vary by region and season. (top) Historically, the Great Plains and the northeastern United States have experienced increased precipitation while the Southwest has experienced a decrease for the period 1986–2015 relative to 1901–1960. (middle and bottom) In the future, under the higher scenario (RCP8.5), the northern United States, including Alaska, is projected to receive more precipitation, especially in the winter and spring by the period 2070–2099 (relative to 1901–1960 for the contiguous United States and 1925–1960 for Alaska, Hawai'i, Puerto Rico, and the U.S. Virgin Islands). Parts of the southwestern United States are projected to receive less precipitation in the winter and spring. Areas with red dots show where projected changes are large compared to natural variations; areas that are hatched show where changes are small and relatively insignificant. Source: adapted from Easterling et al. 2017.[94]

Observed and Projected Change in Heavy Precipitation

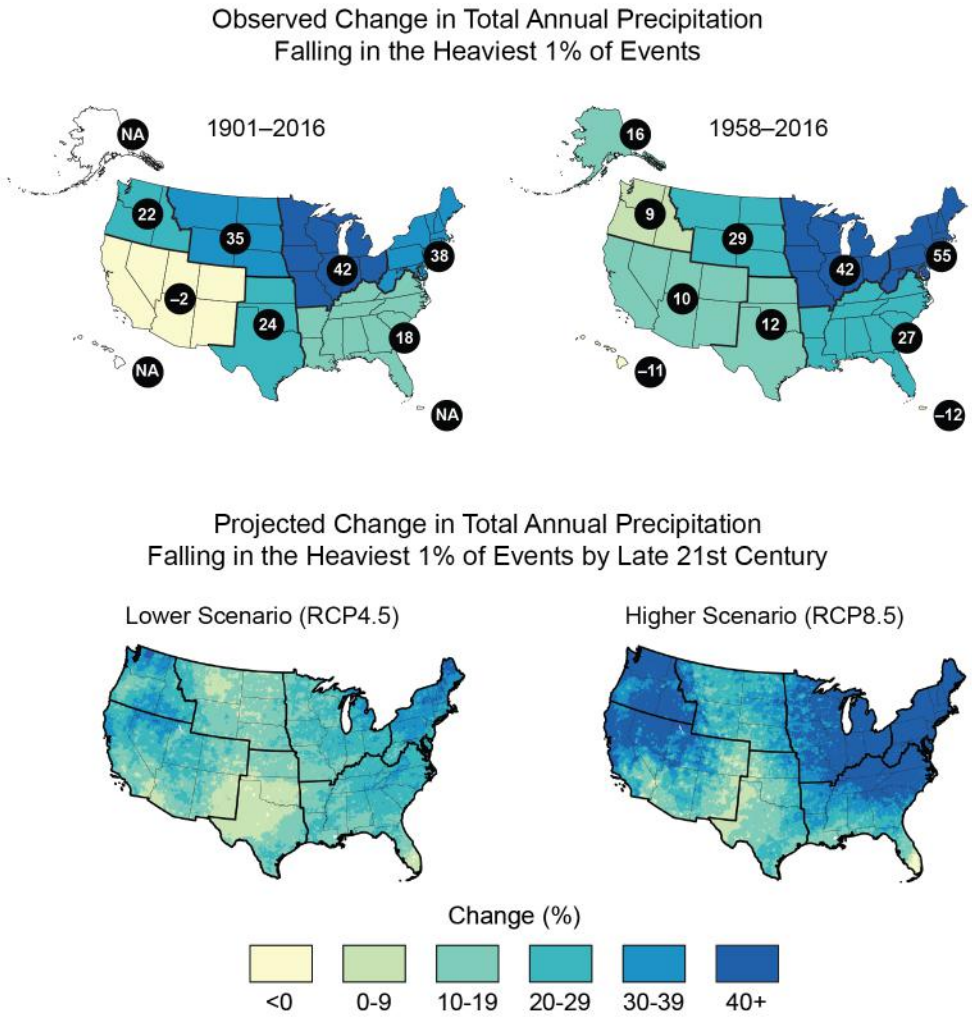


Figure 2.6: Heavy precipitation is becoming more intense and more frequent across most of the United States, particularly in the Northeast and Midwest, and these trends are projected to continue in the future. This map shows the observed (top; numbers in black circles give the percentage change) and projected (bottom) change in the amount of precipitation falling in the heaviest 1% of events (99th percentile of the distribution). Observed historical trends are quantified in two ways. The observed trend for 1901–2016 (top left) is calculated as the difference between 1901–1960 and 1986–2016. The values for 1958–2016 (top right), a period with a denser station network, are linear trend changes over the period. The trends are averaged over each National Climate Assessment region. Projected future trends are for a lower (RCP4.5, left) and a higher (RCP8.5, right) scenario for the period 2070–2099 relative to 1986–2015. Source: adapted from Easterling et al. 2017.[94] Data for projected changes in heavy precipitation were not available for Alaska, Hawai'i, or the U.S. Caribbean. Sources: (top) adapted from Easterling et al. 2017; (bottom) NOAA NCEI, CICS-NC, and NEMAC.

Trends in related types of extreme events, such as floods, are more difficult to discern (e.g., Hirsch and Ryberg 2012, Hodgkins et al. 2017[99,100]). Although extreme precipitation is one of the controlling factors in flood statistics, a variety of other compounding factors, including local land use, land-cover changes, and water management also play important roles. Human-induced warming has not been formally identified as a factor in increased riverine flooding and the timing of any emergence of a future detectable human-caused change is unclear.[101]

Declines have been observed in North America spring snow cover extent and maximum snow depth, as well as snow water equivalent (a measurement of the amount of water stored in snowpack) in the western United States and extreme snowfall years in the southern and western United States.[102,103,104] All are consistent with observed warming, and of these trends,

human-induced warming has been formally identified as a factor in earlier spring melt and reduced snow water equivalent.[101] Projections show large declines in snowpack in the western United States and shifts to more precipitation falling as rain rather than snow in many parts of the central and eastern United States. Under higher future scenarios, assuming no change to current water resources management, snow-dominated watersheds in the western United States are more likely to experience lengthy and chronic hydrological drought conditions by the end of this century.[105,106,107]

Across much of the United States, surface soil moisture is projected to decrease as the climate warms, driven largely by increased evaporation rates due to warmer temperatures. This means that, all else being equal, future droughts in most regions will likely be stronger and potentially last longer. These trends are likely to be strongest in the Southwest and Southern Great Plains, where precipitation is projected to decrease in most seasons (Figure 2.5) and droughts may become more frequent.[101,108,109,110,111,112] Although recent droughts and associated heat waves have reached record intensity in some regions of the United States, the Dust Bowl of the 1930s remains the benchmark drought and extreme heat event in the historical record, and though by some measures drought has decreased over much of the continental United States in association with long-term increases in precipitation (e.g., see McCabe et al. 2017[113]), there is as yet no detectable change in long-term U.S. drought statistics. Further discussion of historical drought is provided in Wehner et al. (2017).[101]

Few analyses consider the relationship across time and space between extreme events; yet it is important to note that the physical and socioeconomic impacts of compound extreme events can be greater than the sum of the parts.[25,114] Compound extremes can include simultaneous heat and drought such as during the 2011–2017 California drought, when 2014, 2015, and 2016 were also the warmest years on record for the state; conditions conducive to the very large wildfires that have already increased in frequency across the western United States and Alaska since the 1980s;[115] or flooding associated with heavy rain over snow or waterlogged ground, which is also projected to increase in the northern contiguous United States.[116]

Key Message 7

Rapid Arctic Change

In the Arctic, annual average temperatures have increased more than twice as fast as the global average, accompanied by thawing permafrost and loss of sea ice and glacier mass. Arctic-wide glacial and sea ice loss is expected to continue; by mid-century, it is very likely that the Arctic will be nearly free of sea ice in late summer. Permafrost is expected to continue to thaw over the coming century as well, and the carbon dioxide and methane released from thawing permafrost has the potential to amplify human-induced warming, possibly significantly.

The Arctic is particularly vulnerable to rising temperatures, since so much of it is covered in ice and snow that begin to melt as temperatures cross the freezing point. The more the Arctic warms, the more snow and ice melts, exposing the darker land and ocean underneath. This darker surface absorbs more of the sun's energy than the reflective ice and snow, amplifying the original warming in a self-reinforcing cycle, or positive feedback.

Some of the most rapid observed changes are occurring in Alaska and across the Arctic. Over the last 50 years, for example, annual average

air temperatures across Alaska and the Arctic have increased more than twice as fast as the global average temperature.[117,118,119,120,121,122] As surface temperatures increase, permafrost—previously permanently frozen ground—is thawing and becoming more discontinuous.[123] This triggers another self-reinforcing cycle, the permafrost–carbon feedback, where carbon previously stored in solid form is released from the ground as carbon dioxide and methane (a greenhouse gas 35 times more powerful than CO_2, on a mass basis, over a 100-year time horizon), resulting in additional warming.[25,122] The overall magnitude of the permafrost–carbon feedback is uncertain, but it is very likely that it is already amplifying carbon emissions and human-induced warming and will continue to do so.[124,125,126] Permafrost emissions imply an even greater decrease in emissions from human activities would be required to hold global temperature below a given amount of warming, such as the levels discussed in Box 2.4.

Most arctic glaciers are losing ice rapidly, and in some cases, the rate of loss is accelerating.[127,128,129,130] This contributes to sea level rise and changes in local salinity that can in turn affect local ocean circulation. In Alaska, annual average glacier ice mass for each year since 1984 has been less than the year before, and glacial ice mass is declining in both the northern and southern regions around the Gulf of Alaska.[131] Dramatic changes have occurred across the Greenland ice sheet as well, particularly at its edges. From 2002 to 2016, ice mass was lost at an average rate of 270 billion tons per year on average, or about 0.1% per decade, a rate that has increased in recent years.[131] The effects of warmer air and ocean temperatures on the melting ice sheet can be amplified by other factors, including dynamical feedbacks (faster sliding, greater calving, and increased melting for the part of the ice that is underwater), near-surface ocean warming, and regional ocean and atmospheric circulation changes.[132,133,134,135]

Finally, much of the Arctic region is ocean that is covered by sea ice, and like land ice, sea ice is also melting (Figure 2.7).[122] Since the early 1980s, annual average arctic sea ice extent has decreased by 3.5%–4.1% per decade.[127,136] The annual minimum sea ice extent, which occurs in September of each year, has decreased at an even greater rate of 11%–16% per decade.[137] Remaining ice is also, on average, becoming thinner (Figure 2.7), as less ice survives to subsequent years, and average ice age declines.[137] The sea ice melt season—defined as the number of days between spring melt onset and fall freeze-up—has lengthened across the Arctic by at least five days per decade since 1979.

Melting sea ice does not contribute to sea level rise, but it does have other climate effects. First, sea ice loss contributes to a positive feedback, or self-reinforcing cycle, through changing the albedo or reflectivity of the Arctic's surface. As sea ice, which is relatively reflective, is replaced by darker ocean, more solar radiation is absorbed by the ocean surface. This contributes to a greater rise in Arctic air temperature compared to the global average and affects formation of ice the next winter. Ice loss also acts to freshen the Arctic Ocean, affecting the temperature of the ocean surface layer and how surface heat is distributed through the ocean mixed layer. This also affects ice formation in subsequent seasons, as well as regional wind patterns, clouds, and ocean temperatures. And finally, sea ice loss also impacts key marine ecosystems and species that depend on the ice, from the polar bear to the ring seal,[138,139,140] and the Alaska coastline becomes more vulnerable to erosion when it is not shielded from storms and waves by sea ice.[141]

Diminishing Arctic Sea Ice

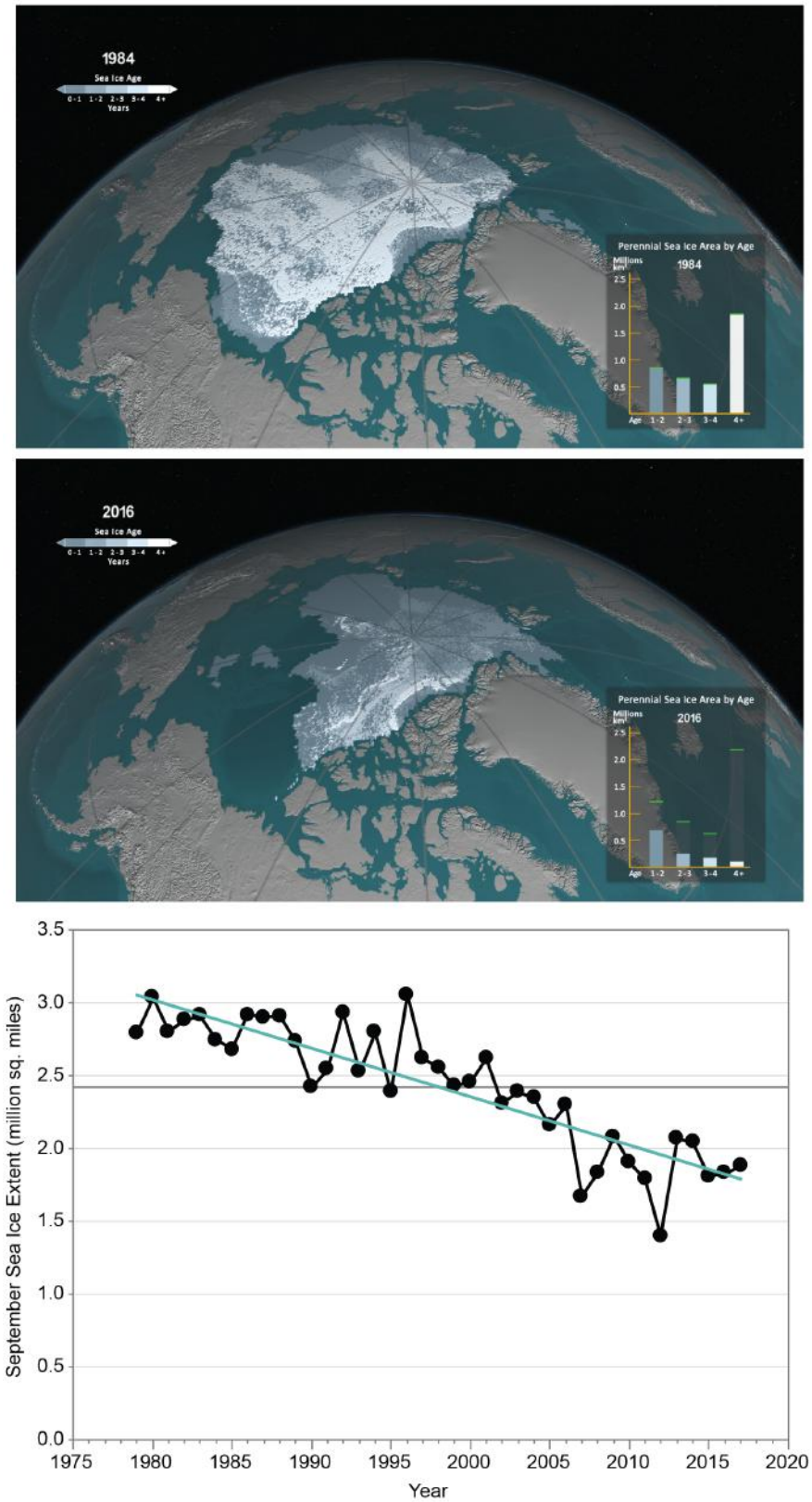


Figure 2.7: As the Arctic warms, sea ice is shrinking and becoming thinner and younger. The top and middle panels show how the summer minimum ice extent and average age, measured in September of each year, changed from 1984 (top) to 2016 (middle). An animation of the complete time series is available at http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4489. September sea ice extent each year from 1979 (when satellite observations began) to 2016, has decreased at a rate of 13.3% ± 2.6% per decade (bottom). The gray line is the 1979–2016 average. Source: adapted from Taylor et al. 2017.[122]

It is virtually certain that human activities have contributed to arctic surface temperature warming, sea ice loss, and glacier mass loss.[122,142,143,144,145,146,147,148] Observed trends in temperature and arctic-wide land and sea ice loss are expected to continue through the 21st century. It is very likely that by mid-century the Arctic Ocean will be almost entirely free of sea ice by late summer for the first time in about 2 million years.[26,149] As climate models have tended to under-predict recent sea ice loss,[143] it is possible this will happen before mid-century.

Key Message 8

Changes in Severe Storms

Human-induced change is affecting atmospheric dynamics and contributing to the poleward expansion of the tropics and the northward shift in Northern Hemisphere winter storm tracks since 1950. Increases in greenhouse gases and decreases in air pollution have contributed to increases in Atlantic hurricane activity since 1970. In the future, Atlantic and eastern North Pacific hurricane rainfall and intensity are projected to increase, as are the frequency and severity of landfalling "atmospheric rivers" on the West Coast.

Changes that occur in one part or region of the climate system can affect others. One of the key ways this is happening is through changes in atmospheric circulation patterns. While the Arctic may seem remote to many, for example, disruptions to the natural cycles of arctic sea ice, land ice, surface temperature, snow cover, and permafrost affect the amount of warming, sea level change, carbon cycle impacts, and potentially even weather patterns in the lower 48 states. Recent studies have linked record warm temperatures in the Arctic to changes in atmospheric circulation patterns in the midlatitudes.[122,150]

Observed changes in other aspects of atmospheric circulation include the northward shift in winter storm tracks since detailed observations began in the 1950s and an associated poleward shift of the subtropical dry zones.[151,152,153] In the future, some studies show increases in the frequency of the most intense winter storms over the northeastern United States (e.g., Colle et al. 2013[154]). Regarding the influence of arctic warming on midlatitude weather, two studies suggest that arctic warming could be linked to the frequency and intensity of severe winter storms in the United States;[155,156] another study shows an influence of arctic warming on summer heat waves and large storms.[157] Other studies show mixed results (e.g., Barnes and Polvani 2015, Perlwitz et al. 2015, Screen et al. 2015[158,159,160]), however, and the nature and magnitude of the influence of arctic warming on U.S. weather over the coming decades remain open questions.

There is no question, however, that the effects of human-induced warming have the potential to affect weather patterns around the world. Changes in the subtropics can also impact the rest of the globe, including the United States. There is growing evidence that the tropics have expanded poleward by about 70 to 200 miles in each hemisphere since satellite measurements began in 1979, with an accompanying shift of the subtropical dry zones, midlatitude jets, and both midlatitude and tropical cyclone tracks.[153,161,162] Human activities have played a role in the change, and although it is not yet possible to separate the magnitude of the human contribution relative to natural variability,[15] these trends are expected to continue over the coming century.

Box 2.5: The 2017 Atlantic Hurricane Season

The severity of the 2017 Atlantic hurricane season was consistent with a combination of natural and human-caused variability on decadal and longer time scales.

The 2017 Atlantic hurricane season tied the record for the most named storms reaching hurricane strength (Figure 2.8); however, the number of storms was within the range of observed historical variability and does not alter the conclusion that climate change is unlikely to increase the overall number of storms on average. At the same time, certain aspects of the 2017 season were unprecedented, and at least two of these aspects are consistent with what might be expected as the planet warms.

First, the ability of four hurricanes—Harvey, Irma, Jose, and Maria (Figure 2.9)—to rapidly reach and maintain very high intensity was anomalous and, in one case, unprecedented. This is consistent with the expectation of stronger storms in a warmer world. All four of these hurricanes experienced rapid intensification, and Irma shattered the existing record for the length of time over which it sustained winds of 185 miles per hour.

Second, the intensity of heavy rain, including heavy rain produced by tropical cyclones, increases in a warmer world (Figure 2.6). Easterling et al. (2017)[94] concluded that the heaviest rainfall amounts from intense storms, including hurricanes, have increased by 6% to 7%, on average, compared to what they would have been a century ago. In particular, both Harvey and Maria were distinguished by record-setting rainfall amounts. Harvey's multiday total rainfall likely exceeded that of any known historical storm in the continental United States, while Maria's rainfall intensity was likely even greater than Harvey's, with some locations in Puerto Rico receiving multiple feet of rain in just 24 hours.

Much of the record-breaking rainfall totals associated with Hurricane Harvey were due to its slow-moving, anomalous track and its proximity to the Gulf of Mexico, which provided a continuous source of moisture. No studies have specifically examined whether the likelihood of hurricanes stalling near land is affected by climate change, and more general research on weather patterns and climate change suggests the possibility of competing influences.[157,161,236,237]

However, Harvey's total rainfall was likely compounded by warmer surface water temperatures feeding the direct deep tropical trajectories historically associated with extreme precipitation in Texas,[238] and these warmer temperatures are partly attributable to human-induced climate change. Initial analyses suggest that the human-influenced contribution to Harvey's rainfall that occurred in the most affected areas was significantly greater than the 5% to 7% increase expected from the simple thermodynamic argument that warmer air can hold more water vapor.[216,218] One study estimated total rainfall amount to be increased as a result of human-induced climate change by at least 19% with a best estimate of 38%,[216] and another study found the three-day rainfall to be approximately 15% more intense and the event itself three times more likely.[217]

Box 2.5: The 2017 Atlantic Hurricane Season, *continued*

2017 Tropical Cyclone Tracks

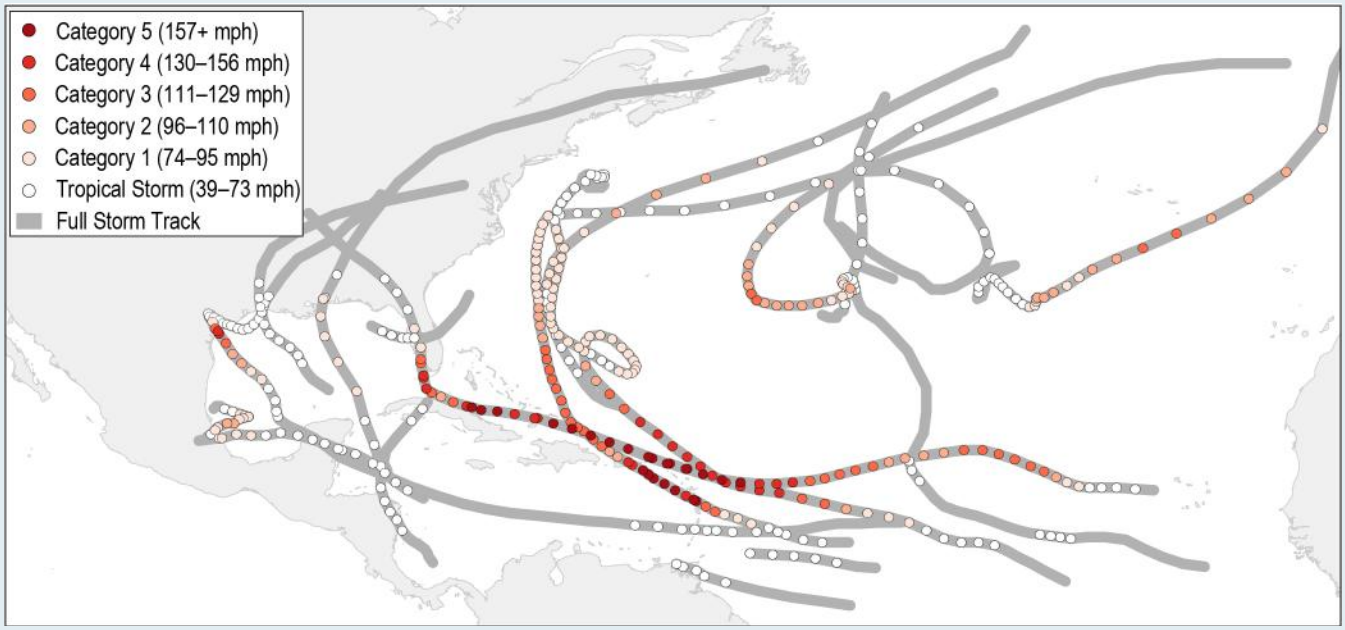


Figure 2.8: Tropical cyclone tracks for the 2017 Atlantic hurricane season. Data are based on the preliminary "operational best-track" provided by the NOAA National Hurricane Center and may change slightly after post-season reanalysis is completed. Sources: NOAA NCEI and ERT, Inc.

Notable 2017 Hurricanes

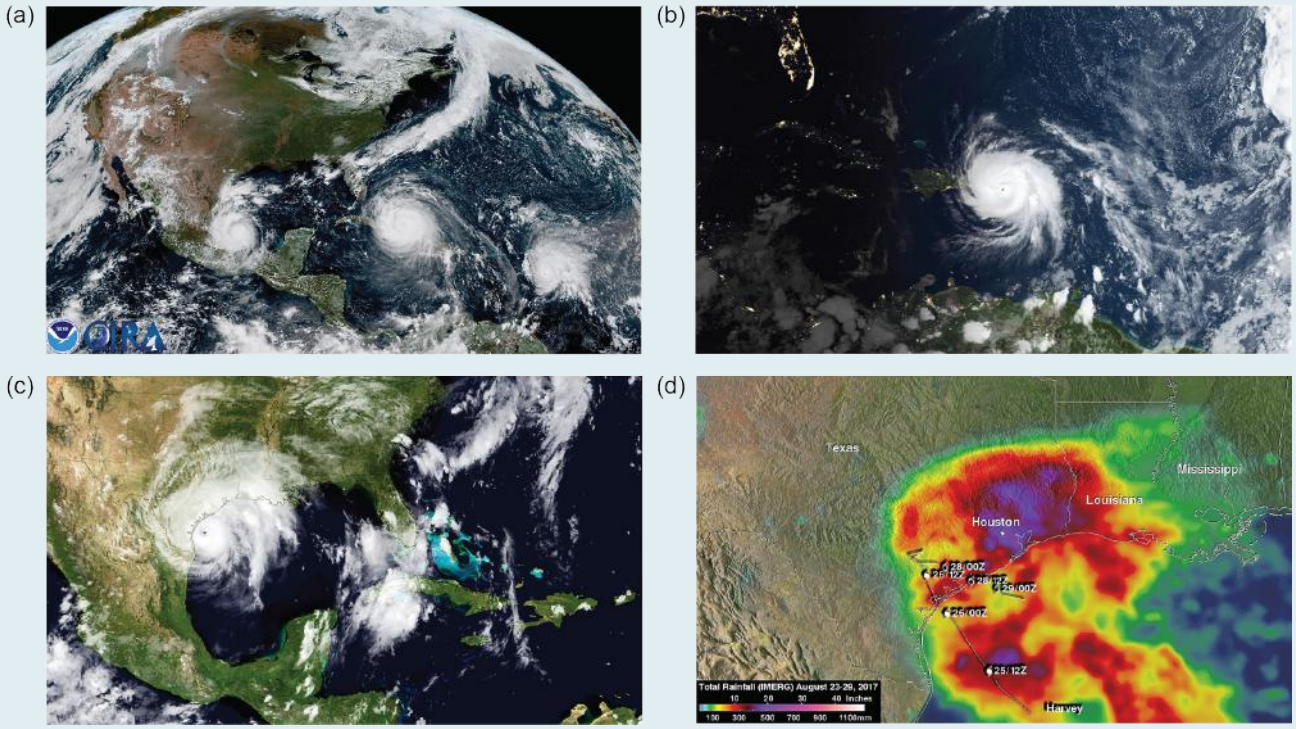


Figure 2.9: (a) Visible imagery from the GOES satellite shows Hurricanes Katia (west), Irma (center) and Jose (east) stretched across the Atlantic on September 8, 2017; (b) Hurricane Maria about to make landfall over Puerto Rico on September 19, 2017; (c) Hurricane Harvey making landfall in Texas on August 23, 2017; and (d) rainfall totals from August 23 to 27 over southeastern Texas and Louisiana. Sources: (a) NOAA CIRA; (b–d) NASA.

Landfalling "atmospheric rivers" are narrow streams of moisture that account for 30%–40% of precipitation and snowpack along the western coast of the United States. They are associated with severe flooding events in California and other western states. As the world warms, the frequency and severity of these events are likely to increase due to increasing evaporation and higher atmospheric water vapor levels in the atmosphere.[101,163,164,165]

Human-caused emissions of greenhouse gases and air pollutants have also affected observed ocean–atmosphere variability in the Atlantic Ocean, and these changes have contributed to the observed increasing trend in North Atlantic tropical cyclone activity since the 1970s[166] (see also review by Sobel et al. 2016[167]). In a warmer world, there will be a greater potential for stronger tropical cyclones (also known as hurricanes and typhoons, depending on the region) in all ocean basins.[15,166,168,169,170,171] Climate model simulations indicate an increase in global tropical cyclone intensity in a warmer world, as well as an increase in the number of very intense tropical cyclones, consistent with current scientific understanding of the physics of the climate system.[15,166,168,169,170,172] In the future, the total number of tropical storms is generally projected to remain steady, or even decrease, but the most intense storms are generally projected to become more frequent, and the amount of rainfall associated with a given storm is also projected to increase.[170] This in turn increases the risk of freshwater flooding along the coasts and secondary effects such as landslides. Though scientific confidence in changes in the projected frequency of very strong storms is low to medium, depending on ocean basin, it is important to note that these storms are responsible for the vast majority of damage and mortality associated with tropical storms.

Extreme events such as tornadoes and severe thunderstorms occur over much shorter time periods and smaller areas than other extreme phenomena such as heat waves, droughts, and even tropical cyclones. This makes it difficult to detect trends and develop future projections[172,173] (see Box 2.6). Compared to damages from other types of extreme weather, those occurring due to thunderstorm-related weather hazards have increased the most since 1980,[174] and there is some indication that, in a warmer world, the number of days with conditions conducive to severe thunderstorm activity is likely to increase.[175,176,177]

Box 2.6: Severe Weather

Observed trends and projections of future changes in severe thunderstorms, tornadoes, hail, and strong wind events are uncertain.

Observed and projected future increases in certain types of extreme weather, such as heavy rainfall and extreme heat, can be directly linked to a warmer world. Other types of extreme weather, such as tornadoes, hail, and thunderstorms, are also exhibiting changes that may be related to climate change, but scientific understanding is not yet detailed enough to confidently project the direction and magnitude of future change.[172]

For example, tornado activity in the United States has become more variable, particularly over the 2000s (e.g., Tippett 2014, Elsner et al. 2015[239,240]), with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days.[241] Although the United States has experienced several significant thunderstorm wind events (sometimes referred to as "derechos") in recent years, there are not enough observations to determine whether there are any long-term trends in their frequency or intensity.[242]

Modeling studies consistently suggest that the frequency and intensity of severe thunderstorms in the United States could increase as climate changes,[177,243,244,245] particularly over the U.S. Midwest and Southern Great Plains during spring.[177] There is some indication that the atmosphere will become more conducive to severe thunderstorm formation and increased intensity, but confidence in the model projections is low. Similarly, there is only low confidence in observations that storms have already become stronger or more frequent. Much of the lack of confidence comes from the difficulty in both monitoring and modeling small-scale and short-lived phenomena.

Key Message 9

Increases in Coastal Flooding

Regional changes in sea level rise and coastal flooding are not evenly distributed across the United States; ocean circulation changes, sinking land, and Antarctic ice melt will result in greater-than-average sea level rise for the Northeast and western Gulf of Mexico under lower scenarios and most of the U.S. coastline other than Alaska under higher scenarios. Since the 1960s, sea level rise has already increased the frequency of high tide flooding by a factor of 5 to 10 for several U.S. coastal communities. The frequency, depth, and extent of tidal flooding are expected to continue to increase in the future, as is the more severe flooding associated with coastal storms, such as hurricanes and nor'easters.

Along U.S. coastlines, how much and how fast sea level rises will not just depend on global trends; it will also be affected by changes in ocean circulation, land elevation, and the rotation and the gravitational field of Earth, which are affected by how much land ice melts, and where.

The primary concern related to ocean circulation is the potential slowing of the Atlantic Ocean Meridional Overturning Circulation (AMOC). An AMOC slowdown would affect poleward heat transport, regional climate, sea level rise along the East Coast of the United States, and the overall response of the Earth's climate system to human-induced change.[34,178,179,180,181]

The AMOC moves warm, salty water from lower latitudes poleward along the surface to the northern Atlantic. This aspect of the AMOC

is also known as the Gulf Stream. In the northern Atlantic, the water cools, sinks, and returns southward as deep waters. AMOC strength is controlled by the rate of sinking within the North Atlantic, which is in turn affected by the rate of heat loss from the ocean to the atmosphere. As the atmosphere warms, surface waters entering the North Atlantic may release less heat and become diluted by increased freshwater melt from Greenland and Northern Hemisphere glaciers. Both of these factors would slow the rate of sinking and weaken the entire AMOC.

Though observational data have been insufficient to determine if a long-term slowdown in the AMOC began during the 20th century,[31,182] one recent study quantifies a 15% weakening since the mid-20th century[183] and another, a weakening over the last 150 years.[184] Over the next few decades, however, it is very likely that the AMOC will weaken. Under the lower RCP4.5 scenario, climate model simulations suggest the AMOC might ultimately stabilize, though bias-corrected simulations continue to show a long-term risk.[180] Under the higher RCP8.5 scenario, projections suggest the AMOC would continue to weaken throughout the century, increasing the probability of an AMOC shutdown (see Box 2.4).[26,180,185]

For almost all future global average sea level rise scenarios of the Interagency Sea Level Rise Taskforce,[76] relative sea level rise is projected to be greater than the global average along the coastlines of the U.S. Northeast and the western Gulf of Mexico due to the effects of ocean circulation changes and sinking land. In addition, with the exception of Alaska, almost all U.S. coastlines are projected to experience higher-than-average sea level rise in response to Antarctic ice loss. Higher global average sea level rise scenarios imply higher levels of Antarctic ice loss; under higher scenarios, then, it is likely that sea level rise along all U.S. coastlines, except Alaska, would be greater than the global average. Along portions of the Alaska coast, especially its southern coastline, relative sea levels are dropping as land uplifts in response to glacial isostatic adjustment (the ongoing movement of land that was once burdened by ice-age glaciers) and retreat of the Alaska glaciers over the last several decades. Future rise amounts are projected to be less than along other U.S. coastlines due to continued uplift and other effects stemming from past and future glacier shrinkage.

Due to sea level rise, daily tidal flooding events capable of causing minor damage to infrastructure have already become 5 to 10 times more frequent since the 1960s in several U.S. coastal cities, and flooding rates are accelerating in over 25 Atlantic and Gulf Coast cities.[186,187,188] For much of the U.S. Atlantic coastline, a local sea level rise of 1.0 to 2.3 feet (0.3 to 0.7 m) would be sufficient to turn nuisance high tide events into major destructive floods.[189] Coastal risks may be further exacerbated as sea level rise increases the frequency and extent of extreme coastal flooding and erosion associated with U.S. coastal storms, such as hurricanes and nor'easters. For instance, the projected increase in the intensity of hurricanes in the North Atlantic could increase the probability of extreme flooding along most U.S. Atlantic and Gulf Coast states beyond what would be projected based on relative sea level rise alone—although it is important to note that this risk could be either offset or amplified by other factors, such as changes in storm frequency or tracks (e.g., Knutson et al. 2013, 2015[170,190]).

Key Message 10

Long-Term Changes

The climate change resulting from human-caused emissions of carbon dioxide will persist for decades to millennia. Self-reinforcing cycles within the climate system have the potential to accelerate human-induced change and even shift Earth's climate system into new states that are very different from those experienced in the recent past. Future changes outside the range projected by climate models cannot be ruled out, and due to their systematic tendency to underestimate temperature change during past warm periods, models may be more likely to underestimate than to overestimate long-term future change.

Humanity's effect on Earth's climate system since the start of the industrial era, through the large-scale combustion of fossil fuels, widespread deforestation, and other activities, is unprecedented. Atmospheric carbon dioxide concentrations are now higher than at any time in the last 3 million years,[191] when both global average temperature and sea level were significantly higher than today.[24] One possible analog for the rapid pace of change occurring today is the relatively abrupt warming of 9°–14°F (5°–8°C) that occurred during the Paleocene-Eocene Thermal Maximum (PETM), approximately 55–56 million years ago.[192,193,194,195] Although there were significant differences in both background conditions and factors affecting climate during the PETM, it is estimated that the rate of maximum sustained carbon release was less than 1.1 gigatons of carbon (GtC) per year (about a tenth of present-day emissions rates). Present-day emissions of nearly 10 GtC per year suggest that there is no analog for this century any time in at least the last 50 million years. Moreover, continued growth in carbon emissions over this century and beyond would lead to atmospheric CO_2 concentrations not experienced in tens to hundreds of millions of years[55,195] (see Hayhoe et al. 2017[24] for further discussion of paleoclimate analogs for present and near-future conditions).

Most of the climate projections used in this assessment are based on simulations by global climate models (GCMs). These comprehensive, state-of-the-art mathematical and computer frameworks use fundamental physics, chemistry, and biology to represent many important aspects of Earth's climate and the processes that occur within and between them (see Box 2.7).[24] However, there are still elements of the earth system that GCMs do not capture well.[196] Self-reinforcing cycles or feedbacks within the climate system have the potential to amplify and accelerate human-induced climate change. As discussed in Kopp et al. (2017),[25] they may even shift Earth's climate system, in part or in whole, into new states that are very different from those experienced in the recent past. Tipping elements are subcomponents of the earth system that can be stable in multiple different states and can be "tipped" between these states by small changes in forcing, amplified by self-reinforcing cycles. Tipping point events may occur when such a threshold is crossed in the climate system (e.g., Lenton et al. 2008, Kopp et al. 2016[197,198]). Some of the self-reinforcing cycles that lead to potential state shifts, such as an ice-free Arctic, can be modeled and quantified; others can be identified but have not yet been quantified, such as changes to cloudiness driven by changes in large-scale patterns of atmospheric circulation;[199] and some are probably still unknown.[25]

Box 2.7: Climate Models and Downscaling

Projections of future changes are based on simulations from global climate models, downscaled to higher resolutions more relevant to local- to regional-scale impacts.

The projections of future change used in this assessment come from global climate models (GCMs) that reproduce key processes in Earth's climate system using fundamental scientific principles. GCMs were previously referred to as "general circulation models" when they included only the physics needed to simulate the general circulation of the atmosphere. Today, global climate models simulate many more aspects of the climate system: atmospheric chemistry and particles, soil moisture and vegetation, land and sea ice cover, and increasingly, an interactive carbon cycle and/or biogeochemistry. Models that include this last component are also referred to as Earth System Models (ESMs), and climate models are constantly being expanded to include more of the physics, chemistry, and increasingly, the biology and biogeochemistry at work in the climate system (Figure 2.10; see also Hayhoe et al. 2017,[24] Section 4.3).

The ability to accurately reproduce key aspects of Earth's climate varies across climate models. In addition, many models share model components or code, so their simulations do not represent entirely independent projections. The Coupled Model Intercomparison Project, Phase 5 (CMIP5) provides a publicly available dataset of simulations from nearly all the world's climate models. As discussed in CSSR,[246] most NCA4 projections use a weighted multimodel average of the CMIP5 models based on a combination of model skill and model independence to provide multimodel ensemble projections of future temperature, precipitation, and other climate variables.

The resolution of global models has increased significantly over time. Even the latest experimental high-resolution simulations, however, are unable to simulate all of the important fine-scale processes occurring at regional to local scales. Instead, a range of methods, generally referred to as "downscaling," are typically used to correct systematic biases in global projections and generate the higher-resolution information required for some impact assessments.[24]

There are two main types of downscaling: 1) dynamical downscaling, which uses regional climate models (RCMs) to calculate the response of regional climate processes to global change over a limited area and 2) empirical statistical downscaling models (ESDMs), which develop statistical relationships between real-world observations and historical global model output, then use these relationships to downscale future projections. Although dynamical and statistical methods can be combined into a hybrid framework, many assessments still tend to rely on one or the other type of downscaling, where the choice is based on the needs of the assessment. Many of the projections shown in this report, for example, are either based on the original GCM simulations or on the latest CMIP5 simulations that have been statistically downscaled using the LOcalized Constructed Analogs (LOCA) ESDM.[247] It is important to note that while ESDMs effectively remove bias and increase spatial resolution, and while RCMs add additional physical insight at smaller spatial scales by resolving processes such as convection (e.g., Prein et. al 2015[248]), they do not include all the processes relevant to climate at local scales. For further discussion, see Hayhoe et al. (2017),[24] Section 4.3.

Box 2.7: Climate Models and Downscaling, *continued*

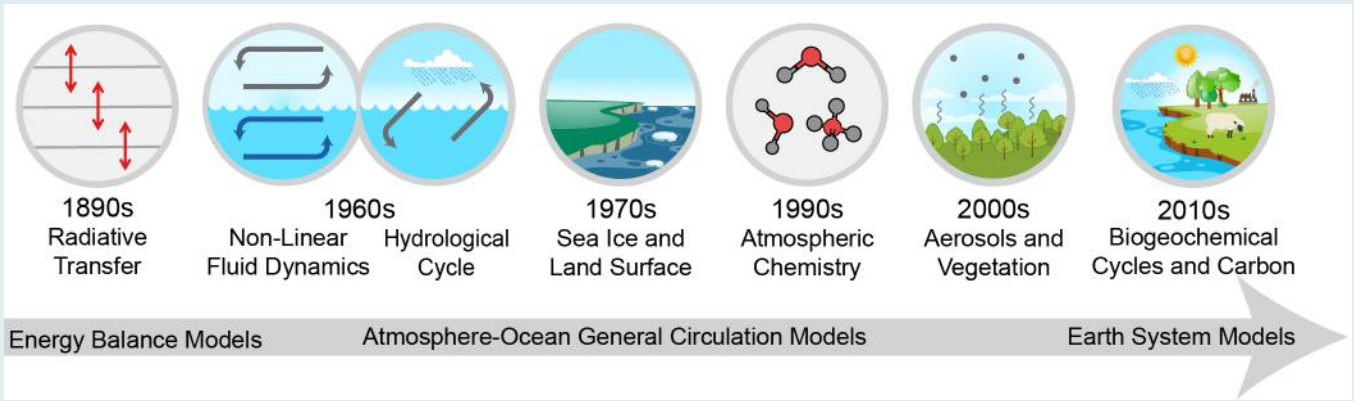


Figure 2.10: As scientific understanding of climate has evolved over the last 120 years, increasing amounts of physics, chemistry, and biology have been incorporated into calculations and, eventually, models. This figure shows when various processes and components of the climate system became regularly included in scientific understanding of global climate and, over the second half of the century as computing resources became available, formalized in global climate models. Source: Hayhoe et al. 2017.[24]

While climate models incorporate important climate processes that can be well quantified, they do not include all of the processes that can contribute to feedbacks, compound extreme events, and abrupt and/or irreversible changes, including key ice sheet processes and arctic carbon reservoirs.[25,185,200] The systematic tendency of climate models to underestimate temperature change during warm paleoclimates[201] suggests that climate models are more likely to underestimate than to overestimate the amount of long-term future change; this is likely to be especially true for trends in extreme events. For this reason, there is significant potential for humankind's planetary experiment to result in surprises—and the further and faster Earth's climate system is changed, the greater the risk of unanticipated changes and impacts, some of which are potentially large and irreversible.

Acknowledgments

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Opening Image Credit

Atmospheric river: NASA Earth Observatory images by Jesse Allen and Joshua Stevens, using VIIRS data from the Suomi National Polar-orbiting Partnership and IMERG data provided courtesy of the Global Precipitation Mission (GPM) Science Team's Precipitation Processing System (PPS).

Traceable Accounts

Process Description

This chapter is based on the collective effort of 32 authors, 3 review editors, and 18 contributing authors comprising the writing team for the *Climate Science Special Report* (CSSR),[208] a featured U.S. Global Change Research Project (USGCRP) deliverable and Volume I of the Fourth National Climate Assessment (NCA4). An open call for technical contributors took place in March 2016, and a federal science steering committee appointed the CSSR team. CSSR underwent three rounds of technical federal review, external peer review by the National Academies of Sciences, Engineering, and Medicine, and a review that was open to public comment. Three in-person Lead Authors Meetings were conducted at various stages of the development cycle to evaluate comments received, assign drafting responsibilities, and ensure cross-chapter coordination and consistency in capturing the state of climate science in the United States. In October 2016, an 11-member core writing team was tasked with capturing the most important CSSR key findings and generating an Executive Summary. The final draft of this summary and the underlying chapters was compiled in June 2017.

The NCA4 Chapter 2 author team was pulled exclusively from CSSR experts tasked with leading chapters and/or serving on the Executive Summary core writing team, thus representing a comprehensive cross-section of climate science disciplines and supplying the breadth necessary to synthesize CSSR content. NCA4 Chapter 2 authors are leading experts in climate science trends and projections, detection and attribution, temperature and precipitation change, severe weather and extreme events, sea level rise and ocean processes, mitigation, and risk analysis. The chapter was developed through technical discussions first promulgated by the literature assessments, prior efforts of USGCRP,[208] e-mail exchanges, and phone consultations conducted to craft this chapter and subsequent deliberations via phone and e-mail exchanges to hone content for the current application. The team placed particular emphasis on the state of science, what was covered in USGCRP,[208] and what is new since the release of the Third NCA in 2014.[1]

Key Message 1

Observed Changes in Global Climate

Global climate is changing rapidly compared to the pace of natural variations in climate that have occurred throughout Earth's history. Global average temperature has increased by about 1.8°F from 1901 to 2016, and observational evidence does not support any credible natural explanations for this amount of warming; instead, the evidence consistently points to human activities, especially emissions of greenhouse or heat-trapping gases, as the dominant cause. (*Very High Confidence*)

Description of evidence base

The Key Message and supporting text summarize extensive evidence documented in the climate science literature and are similar to statements made in previous national (NCA3)[1] and international[249] assessments. The human effects on climate have been well documented through many papers

in the peer reviewed scientific literature (e.g., see Fahey et al. 2017[18] and Knutson et al. 2017[16] for more discussion of supporting evidence).

The finding of an increasingly strong positive forcing over the industrial era is supported by observed increases in atmospheric temperatures (see Wuebbles et al. 2017[10]) and by observed increases in ocean temperatures.[10,57,76] The attribution of climate change to human activities is supported by climate models, which are able to reproduce observed temperature trends when radiative forcing from human activities is included and considerably deviate from observed trends when only natural forcings are included (Wuebbles et al. 2017; Knutson et al. 2017, Figure 3.1[10,16]).

Major uncertainties

Key remaining uncertainties relate to the precise magnitude and nature of changes at global, and particularly regional scales, and especially for extreme events and our ability to simulate and attribute such changes using climate models. The exact effects from land-use changes relative to the effects from greenhouse gas emissions need to be better understood.

The largest source of uncertainty in radiative forcing (both natural and anthropogenic) over the industrial era is quantifying forcing by aerosols. This finding is consistent across previous assessments (e.g., IPCC 2007, IPCC 2013[249,250]).

Recent work has highlighted the potentially larger role of variations in ultraviolet solar irradiance, versus total solar irradiance, in solar forcing. However, this increase in solar forcing uncertainty is not sufficiently large to reduce confidence that anthropogenic activities dominate industrial-era forcing.

Description of confidence and likelihood

There is *very high confidence* for a major human influence on climate.

Assessments of the natural forcings of solar irradiance changes and volcanic activity show with *very high confidence* that both forcings are small over the industrial era relative to total anthropogenic forcing. Total anthropogenic forcing is assessed to have become larger and more positive during the industrial era, while natural forcings show no similar trend.

Key Message 2

Future Changes in Global Climate

Earth's climate will continue to change over this century and beyond (*very high confidence*). Past mid-century, how much the climate changes will depend primarily on global emissions of greenhouse gases and on the response of Earth's climate system to human-induced warming (*very high confidence*). With significant reductions in emissions, global temperature increase could be limited to 3.6°F (2°C) or less compared to preindustrial temperatures (*high confidence*). Without significant reductions, annual average global temperatures could increase by 9°F (5°C) or more by the end of this century compared to preindustrial temperatures (*high confidence*).

Description of evidence base

The Key Message and supporting text summarize extensive evidence documented in the climate science literature and are similar to statements made in previous national (NCA3)[1] and international[249] assessments. The projections for future climate have been well documented through many papers in the peer-reviewed scientific literature (e.g., see Hayhoe et al. 2017[24] for descriptions of the scenarios and the models used).

Major uncertainties

Key remaining uncertainties relate to the precise magnitude and nature of changes at global, and particularly regional, scales and especially for extreme events and our ability to simulate and attribute such changes using climate models. Of particular importance are remaining uncertainties in the understanding of feedbacks in the climate system, especially in ice–albedo and cloud cover feedbacks. Continued improvements in climate modeling to represent the physical processes affecting the Earth's climate system are aimed at reducing uncertainties. Enhanced monitoring and observation programs also can help improve the understanding needed to reduce uncertainties.

Description of confidence and likelihood

There is *very high confidence* for continued changes in climate and *high confidence* for the levels shown in the Key Message.

Key Message 3

Warming and Acidifying Oceans

The world's oceans have absorbed 93% of the excess heat from human-induced warming since the mid-20th century and are currently absorbing more than a quarter of the carbon dioxide emitted to the atmosphere annually from human activities, making the oceans warmer and more acidic (*very high confidence*). Increasing sea surface temperatures, rising sea levels, and changing patterns of precipitation, winds, nutrients, and ocean circulation are contributing to overall declining oxygen concentrations in many locations (*high confidence*).

Description of evidence base

The Key Message and supporting text summarize the evidence documented in climate science literature as summarized in Rhein et al. (2013).[31] Oceanic warming has been documented in a variety of data sources, most notably by the World Ocean Circulation Experiment (WOCE),[251] Argo,[252] and the Extended Reconstructed Sea Surface Temperature v4 (ERSSTv4).[253] There is particular confidence in calculated warming for the time period since 1971 due to increased spatial and depth coverage and the level of agreement among independent sea surface temperature (SST) observations from satellites, surface drifters and ships, and independent studies using differing analyses, bias corrections, and data sources.[20,33,68] Other observations such as the increase in mean sea level rise (see Sweet et al. 2017[76]) and reduced Arctic/Antarctic ice sheets (see Taylor et al. 2017[122]) further confirm the increase in thermal expansion. For the purpose of extending the selected time periods back from 1900 to 2016 and analyzing U.S. regional SSTs, the ERSSTv4[253] is used. For the centennial time scale changes over 1900–2016, warming trends in all regions are statistically

significant with the 95% confidence level. U.S. regional SST warming is similar between calculations using ERSSTv4 in this report and those published by Belkin (2016),[254] suggesting confidence in these findings.

Evidence for oxygen trends arises from extensive global measurements of WOCE after 1989 and individual profiles before that.[43] The first basin-wide dissolved oxygen surveys were performed in the 1920s.[255] The confidence level is based on globally integrated O_2 distributions in a variety of ocean models. Although the global mean exhibits low interannual variability, regional contrasts are large.

Major uncertainties

Uncertainties in the magnitude of ocean warming stem from the disparate measurements of ocean temperature over the last century. There is *high confidence* in warming trends of the upper ocean temperature from 0–700 m depth, whereas there is more uncertainty for deeper ocean depths of 700–2,000 m due to the short record of measurements from those areas. Data on warming trends at depths greater than 2,000 m are even more sparse. There are also uncertainties in the timing and reasons for particular decadal and interannual variations in ocean heat content and the contributions that different ocean basins play in the overall ocean heat uptake.

Uncertainties in ocean oxygen content (as estimated from the intermodel spread) in the global mean are moderate mainly because ocean oxygen content exhibits low interannual variability when globally averaged. Uncertainties in long-term decreases of the global averaged oxygen concentration amount to 25% in the upper 1,000 m for the 1970–1992 period and 28% for the 1993–2003 period. Remaining uncertainties relate to regional variability driven by mesoscale eddies and intrinsic climate variability such as ENSO.

Description of confidence and likelihood

There is very *high confidence* in measurements that show increases in the ocean heat content and warming of the ocean, based on the agreement of different methods. However, long-term data in total ocean heat uptake in the deep ocean are sparse, leading to limited knowledge of the transport of heat between and within ocean basins.

Major ocean deoxygenation is taking place in bodies of water inland, at estuaries, and in the coastal and the open ocean (*high confidence*). Regionally, the phenomenon is exacerbated by local changes in weather, ocean circulation, and continental inputs to the oceans.

Key Message 4

Rising Global Sea Levels

Global average sea level has risen by about 7–8 inches (16–21 cm) since 1900, with almost half this rise occurring since 1993 as oceans have warmed and land-based ice has melted (*very high confidence*). Relative to the year 2000, sea level is very likely to rise 1 to 4 feet (0.3 to 1.3 m) by the end of the century (*medium confidence*). Emerging science regarding Antarctic ice sheet stability suggests that, for higher scenarios, a rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed.

Description of evidence base

Multiple researchers, using different statistical approaches, have integrated tide gauge records to estimate global mean sea level (GMSL) rise since the late 19th century (e.g., Church and White 2006, 2011; Hay et al. 2015; Jevrejeva et al. 2009[61,73,74,256]). The most recent published rate estimates are 1.2 ± 0.2 mm/year[73] or 1.5 ± 0.2 mm/year[74] over 1901–1990. Thus, these results indicate about 4–5 inches (11–14 cm) of GMSL rise from 1901 to 1990. Tide gauge analyses indicate that GMSL rose at a considerably faster rate of about 0.12 inches/year (3 mm/year) since 1993,[73,74] a result supported by satellite data indicating a trend of 0.13 inches/year (3.4 ± 0.4 mm/year) over 1993–2015 (update to Nerem et al. 2010;[75] see also Sweet et al. 2017,[57] Figure 12.3a). These results indicate an additional GMSL rise of about 3 inches (7 cm) since 1990. Thus, total GMSL rise since 1900 is about 7–8 inches (18–21 cm).

The finding regarding the historical context of the 20th-century change is based upon Kopp et al. (2016),[58] who conducted a meta-analysis of geological regional sea level (RSL) reconstructions, spanning the last 3,000 years, from 24 locations around the world, as well as tide gauge data from 66 sites and the tide-gauge-based GMSL reconstruction of Hay et al. (2015).[73] By constructing a spatiotemporal statistical model of these datasets, they identified the common global sea level signal over the last three millennia, and its uncertainties. They found a 95% probability that the average rate of GMSL change over 1900–2000 was greater than during any preceding century in at least 2,800 years.

The lower bound of the *very likely* range is based on a continuation of the observed, approximately 3 mm/year rate of GMSL rise. The upper end of the *very likely* range is based on estimates for a higher scenario (RCP8.5) from three studies producing fully probabilistic projections across multiple RCPs. Kopp et al.(2014)[77] fused multiple sources of information accounting for the different individual process contributing to GMSL rise. Kopp et al. (2016)[58] constructed a semi-empirical sea level model calibrated to the Common Era sea level reconstruction. Mengel et al. (2016)[257] constructed a set of semi-empirical models of the different contributing processes. All three studies show negligible scenario dependence in the first half of this century but increasing in prominence in the second half of the century. A sensitivity study by Kopp et al. (2014),[77] as well as studies by Jevrejeva et al. (2014)[78] and by Jackson and Jevrejeva (2016),[258] used frameworks similar to Kopp et al. (2016)[58] but incorporated an expert elicitation study on ice sheet stability.[259] (This study was incorporated in the main results of Kopp et al. 2014[77] with adjustments for consistency with Church et al. 2013.[56]) These studies extend the *very likely* range for RCP8.5 as high as 5–6 feet (160–180 cm; see Kopp et al. 2014, sensitivity study; Jevrejeva et al. 2014; Jackson and Jevrejeva 2016[77,78,258]).

As described in Sweet et al. (2017),[57] Miller et al. (2013),[260] and Kopp et al. (2017),[77] several lines of arguments exist that support a plausible worst-case GMSL rise scenario in the range of 2.0 m to 2.7 m by 2100. Pfeffer et al. (2008)[261] constructed a "worst-case" 2.0 m scenario, based on acceleration of mass loss from Greenland, that assumed a 30 cm GMSL contribution from thermal expansion. However, Sriver et al. (2012)[262] find a physically plausible upper bound from thermal expansion exceeding 50 cm (an additional ~20-cm increase). The ~60 cm maximum contribution by 2100 from Antarctica in Pfeffer et al. (2008)[261] could be exceeded by ~30 cm, assuming the 95th percentile for Antarctic melt rate (~22 mm/year) of the Bamber and Aspinall (2013)[259] expert elicitation study is achieved by 2100 through a linear growth in melt rate. The Pfeffer et al. (2008)[261]

study did not include the possibility of a net decrease in land-water storage due to groundwater withdrawal; Church et al. (2013)[56] find a likely land-water storage contribution to 21st century GMSL rise of –1 cm to +11 cm. These arguments all point to the physical plausibility of GMSL rise in excess of 8 feet (240 cm).

Additional arguments come from model results examining the effects of marine ice-cliff collapse and ice-shelf hydro-fracturing on Antarctic loss rates.[80] To estimate the effect of incorporating the DeConto and Pollard (2016)[80] projections of Antarctic ice sheet melt, Kopp et al. (2017)[81] substituted the bias-corrected ensemble of DeConto and Pollard[80] into the Kopp et al. (2014)[77] framework. This elevates the projections for 2100 to 3.1–8.9 feet (93–243 cm) for RCP8.5, 1.6–5.2 feet (50–158 cm) for RCP4.5, and 0.9–3.2 feet (26–98 cm) for RCP2.6. DeConto and Pollard (2016)[80] is just one study, not designed in a manner intended to produce probabilistic projections, and so these results cannot be used to ascribe probability; they do, however, support the physical plausibility of GMSL rise in excess of 8 feet.

Very likely ranges, 2030 relative to 2000 in cm (feet)

	Kopp et al. (2014)[77]	Kopp et al. (2016)[58]	Kopp et al. (2017)[81] DP16	Mengel et al. (2016)[257]
RCP8.5 (higher)	11–18 (0.4–0.6)	8–15 (0.3–0.5)	6–22 (0.2–0.7)	7–12 (0.2–0.4)
RCP4.5 (lower)	10–18 (0.3–0.6)	8–15 (0.3–0.5)	6–23 (0.2–0.8)	7–12 (0.2–0.4)
RCP2.6 (very low)	10–18 (0.3–0.6)	8–15 (0.3–0.5)	6–23 (0.2–0.8)	7–12 (0.2–0.4)

Very likely ranges, 2050 relative to 2000 in cm (feet)

	Kopp et al. (2014)[77]	Kopp et al. (2016)[58]	Kopp et al. (2017)[81] DP16	Mengel et al. (2016)[257]
RCP8.5 (higher)	21–38 (0.7–1.2)	16–34 (0.5–1.1)	17–48 (0.6–1.6)	15–28 (0.5–0.9)
RCP4.5 (lower)	18–35 (0.6–1.1)	15–31 (0.5–1.0)	14–43 (0.5–1.4)	14–25 (0.5–0.8)
RCP2.6 (very low)	18–33 (0.6–1.1)	14–29 (0.5–1.0)	12–41 (0.4–1.3)	13–23 (0.4–0.8)

Very likely ranges, 2100 relative to 2000 in cm (feet)

	Kopp et al. (2014)[77]	Kopp et al. (2016)[58]	Kopp et al. (2017)[81] DP16	Mengel et al. (2016)[257]
RCP8.5 (higher)	55–121 (1.8–4.0)	52–131 (1.7–4.3)	93–243 (3.1–8.0)	57–131 (1.9–4.3)
RCP4.5 (lower)	36–93 (1.2–3.1)	33–85 (1.1–2.8)	50–158 (1.6–5.2)	37–77 (1.2–2.5)
RCP2.6 (very low)	29–82 (1.0–2.7)	24–61 (0.8–2.0)	26–98 (0.9–3.2)	28–56 (0.9–1.8)

Major uncertainties

Uncertainties in reconstructed GMSL change relate to the sparsity of tide gauge records, particularly before the middle of the 20th century, and to different statistical approaches for estimating GMSL change from these sparse records. Uncertainties in reconstructed GMSL change before the twentieth century also relate to the sparsity of geological proxies for sea level change, the interpretation of these proxies, and the dating of these proxies. Uncertainty in attribution relates to the reconstruction of past changes and the magnitude of unforced variability.

Since NCA3, multiple different approaches have been used to generate probabilistic projections of GMSL rise, conditional upon the RCPs. These approaches are in general agreement. However, emerging results indicate that marine-based sectors of the Antarctic ice sheet are more

unstable than previous modeling indicated. The rate of ice sheet mass changes remains challenging to project.

Description of confidence and likelihood

This Key Message is based upon multiple analyses of tide gauge and satellite altimetry records, on a meta-analysis of multiple geological proxies for pre-instrumental sea level change, and on both statistical and physical analyses of the human contribution to GMSL rise since 1900.

It is also based upon multiple methods for estimating the probability of future sea level change and on new modeling results regarding the stability of marine-based ice in Antarctica.

Confidence is *very high* in the rate of GMSL rise since 1900, based on multiple different approaches to estimating GMSL rise from tide gauges and satellite altimetry. Confidence is *high* in the substantial human contribution to GMSL rise since 1900, based on both statistical and physical modeling evidence. There is *medium confidence* that the magnitude of the observed rise since 1900 is unprecedented in the context of the previous 2,700 years, based on meta-analysis of geological proxy records.

There is *very high* confidence that GMSL rise over the next several decades will be at least as fast as a continuation of the historical trend over the last quarter century would indicate. There is *medium confidence* in the upper end of very likely ranges for 2030 and 2050. Due to possibly large ice sheet contributions, there is *low confidence* in the upper end of very likely ranges for 2100. Based on multiple projection methods, there is *high confidence* that differences between scenarios are small before 2050 but significant beyond 2050.

Key Message 5

Increasing U.S. Temperatures

Annual average temperature over the contiguous United States has increased by 1.2°F (0.7°C) over the last few decades and by 1.8°F (1°C) relative to the beginning of the last century (*very high confidence*). Additional increases in annual average temperature of about 2.5°F (1.4°C) are expected over the next few decades regardless of future emissions, and increases ranging from 3°F to 12°F (1.6°–6.6°C) are expected by the end of century, depending on whether the world follows a higher or lower future scenario, with proportionally greater changes in high temperature extremes (*high confidence*).

Description of evidence base

The Key Message and supporting text summarize extensive evidence documented in the climate science literature. Similar statements about changes exist in other reports (e.g., NCA3,[1] Climate Change Impacts in the United States,[263] SAP 1.1: Temperature trends in the lower atmosphere[264]).

Evidence for changes in U.S. climate arises from multiple analyses of data from in situ, satellite, and other records undertaken by many groups over several decades. The primary dataset for surface temperatures in the United States is nClimGrid,[85,152] though trends are similar in the U.S. Historical Climatology Network, the Global Historical Climatology Network, and other datasets.

Several atmospheric reanalyses (e.g., 20th Century Reanalysis, Climate Forecast System Reanalysis, ERA-Interim, and Modern Era Reanalysis for Research and Applications) confirm rapid warming at the surface since 1979, and observed trends closely track the ensemble mean of the reanalyses.[265] Several recently improved satellite datasets document changes in middle tropospheric temperatures.[7,266] Longer-term changes are depicted using multiple paleo analyses (e.g., Trouet et al. 2013, Wahl and Smerdon 2012[86,267]).

Evidence for changes in U.S. climate arises from multiple analyses of in situ data using widely published climate extremes indices. For the analyses presented here, the source of in situ data is the Global Historical Climatology Network–Daily dataset.[268] Changes in extremes were assessed using long-term stations with minimal missing data to avoid network-induced variability on the long-term time series. Cold wave frequency was quantified using the Cold Spell Duration Index,[269] heat wave frequency was quantified using the Warm Spell Duration Index,[269] and heat wave intensity was quantified using the Heat Wave Magnitude Index Daily.[270] Station-based index values were averaged into 4° grid boxes, which were then area-averaged into a time series for the contiguous United States. Note that a variety of other threshold and percentile-based indices were also evaluated, with consistent results (e.g., the Dust Bowl was consistently the peak period for extreme heat). Changes in record-setting temperatures were quantified, as in Meehl et al. (2016).[13]

Projections are based on global model results and associated downscaled products from CMIP5 for a lower scenario (RCP4.5) and a higher scenario (RCP8.5). Model weighting is employed to refine projections for each RCP. Weighting parameters are based on model independence and skill over North America for seasonal temperature and annual extremes. The multimodel mean is based on 32 model projections that were statistically downscaled using the LOcalized Constructed Analogs technique.[247] The range is defined as the difference between the average increase in the three coolest models and the average increase in the three warmest models. All increases are significant (i.e., more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change).[271]

Major uncertainties

The primary uncertainties for surface data relate to historical changes in station location, temperature instrumentation, observing practice, and spatial sampling (particularly in areas and periods with low station density, such as the intermountain West in the early 20th century). Much research has been done to account for these issues, resulting in techniques that make adjustments at the station level to improve the homogeneity of the time series (e.g., Easterling and Peterson 1995, Menne and Williams 2009[272,273]). Further, Easterling et al. (1996)[274] examined differences in area-averaged time series at various scales for homogeneity-adjusted temperature data versus non-adjusted data and found that when the area reached the scale of the NCA regions, little differences were found. Satellite records are similarly impacted by non-climatic changes such as orbital decay, diurnal sampling, and instrument calibration to target temperatures. Several uncertainties are inherent in temperature-sensitive proxies, such as dating techniques and spatial sampling.

Global climate models are subject to structural and parametric uncertainty, resulting in a range of estimates of future changes in average temperature. This is partially mitigated through the use of model weighting and pattern scaling. Furthermore, virtually every ensemble member of every

model projection contains an increase in temperature by mid- and late-century. Empirical down-scaling introduces additional uncertainty (e.g., with respect to stationarity).

Description of confidence and likelihood

There is *very high confidence* in trends since 1895, based on the instrumental record, since this is a long-term record with measurements made with relatively high precision. There is *high confidence* for trends that are based on surface/satellite agreement since 1979, since this is a shorter record. There is *medium confidence* for trends based on paleoclimate data, as this is a long record but with relatively low precision.

There is *very high confidence* in observed changes in average annual and seasonal temperature and observed changes in temperature extremes over the United States, as these are based upon the convergence of evidence from multiple data sources, analyses, and assessments including the instrumental record.

There is *high confidence* that the range of projected changes in average temperature and temperature extremes over the United States encompasses the range of likely change, based upon the convergence of evidence from basic physics, multiple model simulations, analyses, and assessments.

Key Message 6

Changing U.S. Precipitation

Annual precipitation since the beginning of the last century has increased across most of the northern and eastern United States and decreased across much of the southern and western United States. Over the coming century, significant increases are projected in winter and spring over the Northern Great Plains, the Upper Midwest, and the Northeast (*medium confidence*). Observed increases in the frequency and intensity of heavy precipitation events in most parts of the United States are projected to continue (*high confidence*). Surface soil moisture over most of the United States is likely to decrease (*medium confidence*), accompanied by large declines in snowpack in the western United States (*high confidence*)and shifts to more winter precipitation falling as rain rather than snow (*medium confidence*).

Description of evidence base

The Key Message and supporting text summarize extensive evidence documented in the climate science peer-reviewed literature and previous National Climate Assessments (e.g., Karl et al. 2009, Walsh et al. 2014[88,263]). Evidence of long-term changes in precipitation is based on analysis of daily precipitation observations from the U.S. Cooperative Observer Network (http://www.nws.noaa.gov/om/coop/) and shown in Easterling et al. (2017),[94] Figure 7.1. Published work, such as the Third National Climate Assessment and Figure 7.1,[94] show important regional and seasonal differences in U.S. precipitation change since 1901.

Numerous papers have been written documenting observed changes in heavy precipitation events in the United States (e.g., Kunkel et al. 2003, Groisman et al. 2004[275,276]), which were cited in the Third National Climate Assessment, as well as those cited in this assessment. Although

station-based analyses (e.g., Westra et al. 2013[277]) do not show large numbers of statistically significant station-based trends, area averaging reduces the noise inherent in station-based data and produces robust increasing signals (see Easterling et al. 2017,[94] Figures 7.2 and 7.3). Evidence of long-term changes in precipitation is based on analysis of daily precipitation observations from the U.S. Cooperative Observer Network (http://www.nws.noaa.gov/om/coop/) and shown in Easterling et al. (2017),[94] Figures 7.2, 7.3, and 7.4.

Evidence of historical changes in snow cover extent and reduction in extreme snowfall years is consistent with our understanding of the climate system's response to increasing greenhouse gases. Furthermore, climate models continue to consistently show future declines in snowpack in the western United States. Recent model projections for the eastern United States also confirm a future shift from snowfall to rainfall during the cold season in colder portions of the central and eastern United States. Each of these changes is documented in the peer-reviewed literature and cited in the main text of this chapter.

Evidence of future change in precipitation is based on climate model projections and our understanding of the climate system's response to increasing greenhouse gases, and on regional mechanisms behind the projected changes. In particular, Figure 7.7 in Easterling et al. (2017)[94] documents projected changes in the 20-year return period amount using the LOCA data, and Figure 7.6[94] shows changes in 2-day totals for the 5-year return period using the CMIP5 suite of models. Each figure shows robust changes in extreme precipitation events as they are defined in the figure. However, Figure 7.5[94] shows changes in seasonal and annual precipitation and shows where confidence in the changes is higher based on consistency between the models, and there are large areas where the projected change is uncertain.

Major uncertainties

The main issue that relates to uncertainty in historical trends is the sensitivity of observed precipitation trends to the spatial distribution of observing stations and to historical changes in station location, rain gauges, the local landscape, and observing practices. These issues are mitigated somewhat by new methods to produce spatial grids[152] through time.

This includes the sensitivity of observed snow changes to the spatial distribution of observing stations and to historical changes in station location, rain gauges, and observing practices, particularly for snow. Future changes in the frequency and intensity of meteorological systems causing heavy snow are less certain than temperature changes.

A key issue is how well climate models simulate precipitation, which is one of the more challenging aspects of weather and climate simulation. In particular, comparisons of model projections for total precipitation (from both CMIP3 and CMIP5; see Sun et al. 2015[271]) by NCA3 region show a spread of responses in some regions (e.g., Southwest) such that they are opposite from the ensemble average response. The continental United States is positioned in the transition zone between expected drying in the subtropics and projected wetting in the mid- and higher latitudes. There are some differences in the location of this transition between CMIP3 and CMIP5 models, and thus there remains uncertainty in the exact location of the transition zone.

Description of confidence and likelihood

Confidence is *medium* that precipitation has increased and *high* that heavy precipitation events have increased in the United States. Furthermore, confidence is also *high* that the important regional and seasonal differences in changes documented here are robust.

Based on evidence from climate model simulations and our fundamental understanding of the relationship of water vapor to temperature, confidence is *high* that extreme precipitation will increase in all regions of the United States. However, based on the evidence and understanding of the issues leading to uncertainties, confidence is *medium* that more total precipitation is projected for the northern United States and less for the Southwest.

Based on the evidence and understanding of the issues leading to uncertainties, confidence is *medium* that average annual precipitation has increased in the United States. Furthermore, confidence is also *medium* that the important regional and seasonal differences in changes documented in the text and in Figure 7.1 in Easterling et al. (2017)[94] are robust.

Given the evidence base and uncertainties, confidence is *medium* that snow cover extent has declined in the United States and *medium* that extreme snowfall years have declined in recent years. Confidence is *high* that western U.S. snowpack will decline in the future, and confidence is *medium* that a shift from snow domination to rain domination will occur in the parts of the central and eastern United States cited in the text, as well as that soil moisture in the surface (top 10cm) will decrease.

Key Message 7

Rapid Arctic Change

In the Arctic, annual average temperatures have increased more than twice as fast as the global average, accompanied by thawing permafrost and loss of sea ice and glacier mass (*very high confidence*). Arctic-wide glacial and sea ice loss is expected to continue; by mid-century, it is very likely that the Arctic will be nearly free of sea ice in late summer (*very high confidence*). Permafrost is expected to continue to thaw over the coming century as well, and the carbon dioxide and methane released from thawing permafrost has the potential to amplify human-induced warming, possibly significantly (*high confidence*).

Description of evidence base

Annual average near-surface air temperatures across Alaska and the Arctic have increased over the last 50 years at a rate more than twice the global average. Observational studies using ground-based observing stations and satellites analyzed by multiple independent groups support this finding. The enhanced sensitivity of the arctic climate system to anthropogenic forcing is also supported by climate modeling evidence, indicating a solid grasp on the underlying physics. These multiple lines of evidence provide *very high confidence* of enhanced arctic warming with potentially significant impacts on coastal communities and marine ecosystems.

This aspect of the Key Message is supported by observational evidence from ground-based observing stations, satellites, and data model temperature analyses from multiple sources and

independent analysis techniques.[117,118,119,120,121,136,278] For more than 40 years, climate models have predicted enhanced arctic warming, indicating a solid grasp of the underlying physics and positive feedbacks driving the accelerated arctic warming.[26,279,280] Lastly, similar statements have been made in NCA3,[1] IPCC AR5,[120] and in other arctic-specific assessments such as the Arctic Climate Impacts Assessment[281] and the Snow, Water, Ice and Permafrost in the Arctic assessment report.[129]

Permafrost is thawing, becoming more discontinuous, and releasing carbon dioxide (CO_2) and methane (CH_4). Observational and modeling evidence indicates that permafrost has thawed and released additional CO_2 and CH_4, indicating that the permafrost–carbon feedback is positive, accounting for additional warming of approximately 0.08°C to 0.50°C on top of climate model projections. Although the magnitude and timing of the permafrost–carbon feedback are uncertain due to a range of poorly understood processes (deep soil and ice wedge processes, plant carbon uptake, dependence of uptake and emissions on vegetation and soil type, and the role of rapid permafrost thaw processes such as thermokarst), emerging science and the newest estimates continue to indicate that this feedback is more likely on the larger side of the range. Impacts of permafrost thaw and the permafrost–carbon feedback complicate our ability to limit future temperature changes by adding a currently unconstrained radiative forcing to the climate system.

This part of the Key Message is supported by observational evidence of warming permafrost temperatures and a deepening active layer, in situ gas measurements, laboratory incubation experiments of CO_2 and CH_4 release, and model studies.[126,127,282,283,284,285] Alaska and arctic permafrost characteristics have responded to increased temperatures and reduced snow cover in most regions since the 1980s, with colder permafrost warming faster than warmer permafrost.[127,129,286] Large carbon soil pools (approximately half of the global below-ground organic carbon pool) are stored in permafrost soil,[287,288] with the potential to be released. Thawing permafrost makes previously frozen organic matter available for microbial decomposition. In situ gas flux measurements have directly measured the release of CO_2 and CH_4 from arctic permafrost.[289,290] The specific conditions of microbial decomposition, aerobic or anaerobic, determine the relative production of CO_2 and CH_4. This distinction is significant as CH_4 is a much more powerful greenhouse gas than CO_2.[17] However, incubation studies indicate that 3.4 times more carbon is released under aerobic conditions than anaerobic conditions, leading to a 2.3 times stronger radiative forcing under aerobic conditions.[284] Combined data and modeling studies suggest that the impact of the permafrost–carbon feedback on global temperatures could amount to +0.52° ± 0.38°F (+0.29° ± 0.21°C) by 2100.[124] Chadburn et al. (2017)[291] infer the sensitivity of permafrost area to globally averaged warming to be 1.5 million square miles (4 million square km), constraining a group of climate models with the observed spatial distribution of permafrost; this sensitivity is 20% higher than previous studies. Permafrost thaw is occurring faster than models predict due to poorly understood deep soil, ice wedge, and thermokarst processes.[125,282,285,292] Additional uncertainty stems from the surprising uptake of methane from mineral soils[293] and dependence of emissions on vegetation and soil properties.[294] The observational and modeling evidence supports the Key Message that the permafrost–carbon feedback is positive (i.e., amplifies warming).

Arctic land and sea ice loss observed in the last three decades continues, in some cases accelerating. A diverse range of observational evidence from multiple data sources and independent analysis techniques provides consistent evidence of substantial declines in arctic sea ice extent, thickness, and volume since at least 1979, mountain glacier melt over the last 50 years, and

accelerating mass loss from Greenland. An array of different models and independent analyses indicate that future declines in ice across the Arctic are expected, resulting in late summers in the Arctic very likely becoming ice free by mid-century.

This final aspect of the Key Message is supported by observational evidence from multiple ground-based and satellite-based observational techniques (including passive microwave, laser and radar altimetry, and gravimetry) analyzed by independent groups using different techniques reaching similar conclusions.[127,128,131,136,257,295,296,297]Additionally, the U.S. Geological Survey repeat photography database shows the glacier retreat for many Alaska glaciers (Taylor et al. 2017,[122] Figure 11.4). Several independent model analysis studies using a wide array of climate models and different analysis techniques indicate that sea ice loss will continue across the Arctic, *very likely* resulting in late summers becoming nearly ice-free by mid-century.[26,147,149]

Major uncertainties

The lack of high-quality data and the restricted spatial resolution of surface and ground temperature data over many arctic land regions, coupled with the fact that there are essentially no measurements over the Central Arctic Ocean, hampers the ability to better refine the rate of arctic warming and completely restricts our ability to quantify and detect regional trends, especially over the sea ice. Climate models generally produce an arctic warming between two to three times the global mean warming. A key uncertainty is our quantitative knowledge of the contributions from individual feedback processes in driving the accelerated arctic warming. Reducing this uncertainty will help constrain projections of future arctic warming.

A lack of observations affects not only the ability to detect trends but also to quantify a potentially significant positive feedback to climate warming: the permafrost–carbon feedback. Major uncertainties are related to deep soil and thermokarst processes, as well as the persistence or degradation of massive ice (e.g., ice wedges) and the dependence of CO_2 and CH_4 uptake and production on vegetation and soil properties. Uncertainties also exist in relevant soil processes during and after permafrost thaw, especially those that control unfrozen soil carbon storage and plant carbon uptake and net ecosystem exchange. Many processes with the potential to drive rapid permafrost thaw (such as thermokarst) are not included in current Earth System Models.

Key uncertainties remain in the quantification and modeling of key physical processes that contribute to the acceleration of land and sea ice melting. Climate models are unable to capture the rapid pace of observed sea and land ice melt over the last 15 years; a major factor is our inability to quantify and accurately model the physical processes driving the accelerated melting. The interactions between atmospheric circulation, ice dynamics and thermodynamics, clouds, and specifically the influence on the surface energy budget are key uncertainties. Mechanisms controlling marine-terminating glacier dynamics, specifically the roles of atmospheric warming, seawater intrusions under floating ice shelves, and the penetration of surface meltwater to the glacier bed, are key uncertainties in projecting Greenland ice sheet melt.

Description of confidence and likelihood

Thre is *very high confidence* that the arctic surface and air temperatures have warmed across Alaska and the Arctic at a much faster rate than the global average is provided by the multiple datasets analyzed by multiple independent groups indicating the same conclusion. Additionally,

climate models capture the enhanced warming in the Arctic, indicating a solid understanding of the underlying physical mechanisms.

There is *high confidence* that permafrost is thawing, becoming discontinuous, and releasing CO_2 and CH_4. Physically based arguments and observed increases in CO_2 and CH_4 emissions as permafrost thaws indicate that the feedback is positive. This confidence level is justified based on observations of rapidly changing permafrost characteristics.

There is *very high confidence* that arctic sea and land ice melt is accelerating and mountain glacier ice mass is declining, given the multiple observational sources and analysis techniques documented in the peer-reviewed climate science literature.

Key Message 8

Changes in Severe Storms

Human-induced change is affecting atmospheric dynamics and contributing to the poleward expansion of the tropics and the northward shift in Northern Hemisphere winter storm tracks since the 1950s (*medium to high confidence*). Increases in greenhouse gases and decreases in air pollution have contributed to increases in Atlantic hurricane activity since 1970 (*medium confidence*). In the future, Atlantic and eastern North Pacific hurricane rainfall (*high confidence*) and intensity (*medium confidence*) are projected to increase, as are the frequency and severity of landfalling "atmospheric rivers" on the West Coast (*medium confidence*).

Description of evidence base

The tropics have expanded poleward in each hemisphere over the period 1979–2009 (*medium to high confidence*) as shown by a large number of studies using a variety of metrics, observations, and reanalysis. Modeling studies and theoretical considerations illustrate that human activities like increases in greenhouse gases, ozone depletion, and anthropogenic aerosols cause a widening of the tropics. There is *medium confidence* that human activities have contributed to the observed poleward expansion, taking into account uncertainties in the magnitude of observed trends and a possible large contribution of natural climate variability.

The first part of the Key Message is supported by statements of the previous international IPCC AR5 assessment[120] and a large number of more recent studies that examined the magnitude of the observed tropical widening and various causes.[95,161,298,299,300,301,302,303,304,305] Additional evidence for an impact of greenhouse gas increases on the widening of the tropical belt and poleward shifts of the midlatitude jets is provided by the diagnosis of CMIP5 simulations.[306,307] There is emerging evidence for an impact of anthropogenic aerosols on the tropical expansion in the Northern Hemisphere.[308,309] Recent studies provide new evidence on the significance of internal variability on recent changes in the tropical width.[302,310,311]

Models are generally in agreement that tropical cyclones will be more intense and have higher precipitation rates, at least in most basins. Given the agreement among models and support of theory and mechanistic understanding, there is *medium to high confidence* in the overall

projection, although there is some limitation on confidence levels due to the lack of a supporting detectable anthropogenic contribution to tropical cyclone intensities or precipitation rates.

The second part of the Key Message is also based on extensive evidence documented in the climate science literature and is similar to statements made in previous national (NCA3)[1] and international[249] assessments. Since these assessments, more recent downscaling studies have further supported these assessments (e.g., Knutson et al. 2015[170]), though pointing out that the changes (future increased intensity and tropical cyclone precipitation rates) may not occur in all basins.

Increases in atmospheric river frequency and intensity are expected along the U.S. West Coast, leading to the likelihood of more frequent flooding conditions, with uncertainties remaining in the details of the spatial structure of these systems along the coast (for example, northern vs. southern California). Evidence for the expectation of an increase in the frequency and severity of landfalling atmospheric rivers on the U.S. West Coast comes from the CMIP-based climate change projection studies of Dettinger (2011),[163] Warner et al. (2015),[164] Payne and Magnusdottir (2015),[312] Gao et al. (2015),[165] Radić et al. (2015),[313] and Hagos et al. (2016).[314] The close connection between atmospheric rivers and water availability and flooding is based on the present-day observation studies of Guan et al. (2010),[315] Dettinger (2011),[163] Ralph et al. (2006),[316] Neiman et al. (2011),[317] Moore et al. (2012),[318] and Dettinger (2013).[319]

Major uncertainties

The rate of observed expansion of the tropics depends on which metric is used.[161] The linkages between different metrics are not fully explored. Uncertainties also result from the utilization of reanalysis to determine trends and from limited observational records of free atmosphere circulation, precipitation, and evaporation. The dynamical mechanisms behind changes in the width of the tropical belt (e.g., tropical–extratropical interactions, baroclinic eddies) are not fully understood. There is also a limited understanding of how various climate forcings, such as anthropogenic aerosols, affect the width of the tropics. The coarse horizontal and vertical resolution of global climate models may limit the ability of these models to properly resolve latitudinal changes in the atmospheric circulation. Limited observational records affect the ability to accurately estimate the contribution of natural decadal to multi-decadal variability on observed expansion of the tropics.

A key uncertainty in tropical cyclones (TCs) is the lack of a supporting detectable anthropogenic signal in the historical data to add further confidence to these projections. As such, confidence in the projections is based on agreement among different modeling studies and physical understanding (for example, potential intensity theory for TC intensities and the expectation of stronger moisture convergence, and thus higher precipitation rates, in TCs in a warmer environment containing greater amounts of environmental atmospheric moisture). Additional uncertainty stems from uncertainty in both the projected pattern and magnitude of future SST.[170]

In terms of atmospheric rivers (ARs), a modest uncertainty remains in the lack of a supporting detectable anthropogenic signal in the historical data to add further confidence to these projections. However, the overall increase in ARs projected/expected is based to a very large degree on *very high confidence* that the atmospheric water vapor will increase. Thus, increasing water vapor coupled with little projected change in wind structure/intensity still indicates increases in the frequency/intensity of ARs. A modest uncertainty arises in quantifying the expected change at a

regional level (for example, northern Oregon, versus southern Oregon), given that there are some changes expected in the position of the jet stream that might influence the degree of increase for different locations along the west coast. Uncertainty in the projections of the number and intensity of ARs is introduced by uncertainties in the models' ability to represent ARs and their interactions with climate.

Description of confidence and likelihood

There is *medium to high confidence* that the tropics and related features of the global circulation have expanded poleward is based upon the results of a large number of observational studies, using a wide variety of metrics and datasets, which reach similar conclusions. A large number of studies utilizing modeling of different complexity and theoretical considerations provide compounding evidence that human activities like increases in greenhouse gases, ozone depletion, and anthropogenic aerosols contributed to the observed poleward expansion of the tropics. Climate models forced with these anthropogenic drivers cannot explain the observed magnitude of tropical expansion, and some studies suggest a possibly large contribution of internal variability. These multiple lines of evidence lead to the conclusion of *medium confidence* that human activities contributed to observed expansion of the tropics.

Confidence is rated as *high* in tropical cyclone rainfall projections and *medium* in intensity projections since there are a number of publications supporting these overall conclusions, fairly well-established theory, general consistency among different studies, varying methods used in studies, and still a fairly strong consensus among studies. However, a limiting factor for confidence in the results is the lack of a supporting detectable anthropogenic contribution in observed tropical cyclone data.

There is *low to medium confidence* for increased occurrence of the most intense tropical cyclones for most basins, as there are relatively few formal studies focused on these changes, and the change in occurrence of such storms would be enhanced by increased intensities but reduced by decreased overall frequency of tropical cyclones.

Confidence in this finding on atmospheric rivers is rated as *medium* based on qualitatively similar projections among different studies.

Key Message 9

Increases in Coastal Flooding

Regional changes in sea level rise and coastal flooding are not evenly distributed across the United States; ocean circulation changes, sinking land, and Antarctic ice melt will result in greater-than-average sea level rise for the Northeast and western Gulf of Mexico under lower scenarios and most of the U.S. coastline other than Alaska under higher scenarios (*very high confidence*). Since the 1960s, sea level rise has already increased the frequency of high tide flooding by a factor of 5 to 10 for several U.S. coastal communities. The frequency, depth, and extent of tidal flooding are expected to continue to increase in the future (*high confidence*), as is the more severe flooding associated with coastal storms, such as hurricanes and nor'easters (*low confidence*).

Description of evidence base

The part of the Key Message regarding the existence of geographic variability is based upon a broader observational, modeling, and theoretical literature. The specific differences are based upon the scenarios described by the Federal Interagency Sea Level Rise Task Force.[76] The processes that cause geographic variability in regional sea level (RSL) change are also reviewed by Kopp et al. (2015).[320] Long tide gauge datasets reveal where RSL rise is largely driven by vertical land motion due to glacio-isostatic adjustment and fluid withdrawal along many U.S. coastlines.[321,322] These observations are corroborated by glacio-isostatic adjustment models, by global positioning satellite (GPS) observations, and by geological data (e.g., Engelhart and Horton 2012[323]). The physics of the gravitational, rotational, and flexural "static-equilibrium fingerprint" response of sea level to redistribution of mass from land ice to the oceans is well-established.[324,325] GCM studies indicate the potential for a Gulf Stream contribution to sea level rise in the U.S. Northeast.[326,327] Kopp et al. (2014)[77] and Slangen et al. (2014)[59] accounted for land motion (only glacial isostatic adjustment for Slangen et al.), fingerprint, and ocean dynamic responses. Comparing projections of local RSL change and GMSL change in these studies indicates that local rise is likely to be greater than the global average along the U.S. Atlantic and Gulf Coasts and less than the global average in most of the Pacific Northwest. Sea level rise projections in this report were developed by a Federal Interagency Sea Level Rise Task Force.[76]

The frequency, extent, and depth of extreme event-driven (e.g., 5- to 100-year event probabilities) coastal flooding relative to existing infrastructure will continue to increase in the future as local RSL rises.[57,76,77,328,329,330,331,332,333] These projections are based on modeling studies of future hurricane characteristics and associated increases in major storm surge risk amplification. Extreme flood probabilities will increase regardless of changes in storm characteristics, which may exacerbate such changes. Model-based projections of tropical storms and related major storm surges within the North Atlantic mostly agree that intensities and frequencies of the most intense storms will increase this century.[190,334,335,336,337] However, the projection of increased hurricane intensity is more robust across models than the projection of increased frequency of the most intense storms. A number of models project a decrease in the overall number of tropical storms and hurricanes in the North Atlantic, although high-resolution models generally project increased mean hurricane intensity (e.g., Knutson et al. 2013[190]). In addition, there is model evidence for a change in tropical cyclone tracks in warm years that minimizes the increase in landfalling hurricanes in the U.S. mid-Atlantic or Northeast.[338]

Major uncertainties

Since NCA3,[1] multiple authors have produced global or regional studies synthesizing the major process that causes global and local sea level change to diverge. The largest sources of uncertainty in the geographic variability of sea level change are ocean dynamic sea level change and, for those regions where sea level fingerprints for Greenland and Antarctica differ from the global mean in different directions, the relative contributions of these two sources to projected sea level change.

Uncertainties remain large with respect to the precise change in future risk of a major coastal impact at a specific location from changes in the most intense tropical cyclone characteristics and tracks beyond changes imposed from local sea level rise.

Description of confidence and likelihood

Because of the enumerated physical processes, there is *very high confidence* that RSL change will vary across U.S. coastlines. There is *high confidence* in the likely differences of RSL change from GMSL change under different levels of GMSL change, based on projections incorporating the different relevant processes. There is *low confidence* that the flood risk at specific locations will be amplified from a major tropical storm this century.

Key Message 10

Long-Term Changes

The climate change resulting from human-caused emissions of carbon dioxide will persist for decades to millennia. Self-reinforcing cycles within the climate system have the potential to accelerate human-induced change and even shift Earth's climate system into new states that are very different from those experienced in the recent past. Future changes outside the range projected by climate models cannot be ruled out (*very high confidence*), and due to their systematic tendency to underestimate temperature change during past warm periods, models may be more likely to underestimate than to overestimate long-term future change (*medium confidence*).

Description of evidence base

This Key Message is based on a large body of scientific literature recently summarized by Lenton et al. (2008),[197] NRC (2013),[339] and Kopp et al. (2016).[198] As NRC (2013)[339] states, "A study of Earth's climate history suggests the inevitability of 'tipping points'—thresholds beyond which major and rapid changes occur when crossed—that lead to abrupt changes in the climate system" and "Can all tipping points be foreseen? Probably not. Some will have no precursors, or may be triggered by naturally occurring variability in the climate system. Some will be difficult to detect, clearly visible only after they have been crossed and an abrupt change becomes inevitable." As IPCC AR5 WG1 Chapter 12, Section 12.5.5[26] further states, "A number of components or phenomena within the Earth system have been proposed as potentially possessing critical thresholds (sometimes referred to as tipping points) beyond which abrupt or nonlinear transitions to a different state ensues." Collins et al. (2013)[26] further summarize critical thresholds that can be modeled and others that can only be identified.

This Key Message is also based on the conclusions of IPCC AR5 WG1,[249] specifically Chapter 7;[196] the state of the art of global models is briefly summarized in Hayhoe et al. (2017).[24] This Key Message is also based upon the tendency of global climate models to underestimate, relative to geological reconstructions, the magnitude of both long-term global mean warming and the amplification of warming at high latitudes in past warm climates (e.g., Salzmann et al. 2013, Goldner et al. 2014, Caballeo and Huber 2013, Lunt et al. 2012[199,201,340,341]).

Major uncertainties

The largest uncertainties are 1) whether proposed tipping elements actually undergo critical transitions, 2) the magnitude and timing of forcing that will be required to initiate critical transitions in tipping elements, 3) the speed of the transition once it has been triggered, 4) the characteristics

of the new state that results from such transition, and 5) the potential for new positive feedbacks and tipping elements to exist that are yet unknown.

The largest uncertainties in models are structural: are the models including all the important components and relationships necessary to model the feedbacks and, if so, are these correctly represented in the models?

Description of confidence and likelihood

There is *very high confidence* in the likelihood of the existence of positive feedbacks and tipping elements based on a large body of literature published over the last 25 years that draws from basic physics, observations, paleoclimate data, and modeling.

There is *very high confidence* that some feedbacks can be quantified, others are known but cannot be quantified, and others may yet exist that are currently unknown.

There is *very high confidence* that the models are incomplete representations of the real world; and there is *medium confidence* that their tendency is to under- rather than overestimate the amount of long-term future change.

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3 Water

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3 Water

Levee repair along the San Joaquin River in California, February 2017

Key Message 1

Changes in Water Quantity and Quality

Significant changes in water quantity and quality are evident across the country. These changes, which are expected to persist, present an ongoing risk to coupled human and natural systems and related ecosystem services. Variable precipitation and rising temperature are intensifying droughts, increasing heavy downpours, and reducing snowpack. Reduced snow-to-rain ratios are leading to significant differences between the timing of water supply and demand. Groundwater depletion is exacerbating drought risk. Surface water quality is declining as water temperature increases and more frequent high-intensity rainfall events mobilize pollutants such as sediments and nutrients.

Key Message 2

Deteriorating Water Infrastructure at Risk

Deteriorating water infrastructure compounds the climate risk faced by society. Extreme precipitation events are projected to increase in a warming climate and may lead to more severe floods and greater risk of infrastructure failure in some regions. Infrastructure design, operation, financing principles, and regulatory standards typically do not account for a changing climate. Current risk management does not typically consider the impact of compound extremes (co-occurrence of multiple events) and the risk of cascading infrastructure failure.

Key Message 3

Water Management in a Changing Future

Water management strategies designed in view of an evolving future we can only partially anticipate will help prepare the Nation for water- and climate-related risks of the future. Current water management and planning principles typically do not address risk that changes over time, leaving society exposed to more risk than anticipated. While there are examples of promising approaches to manage climate risk, the gap between research and implementation, especially in view of regulatory and institutional constraints, remains a challenge.

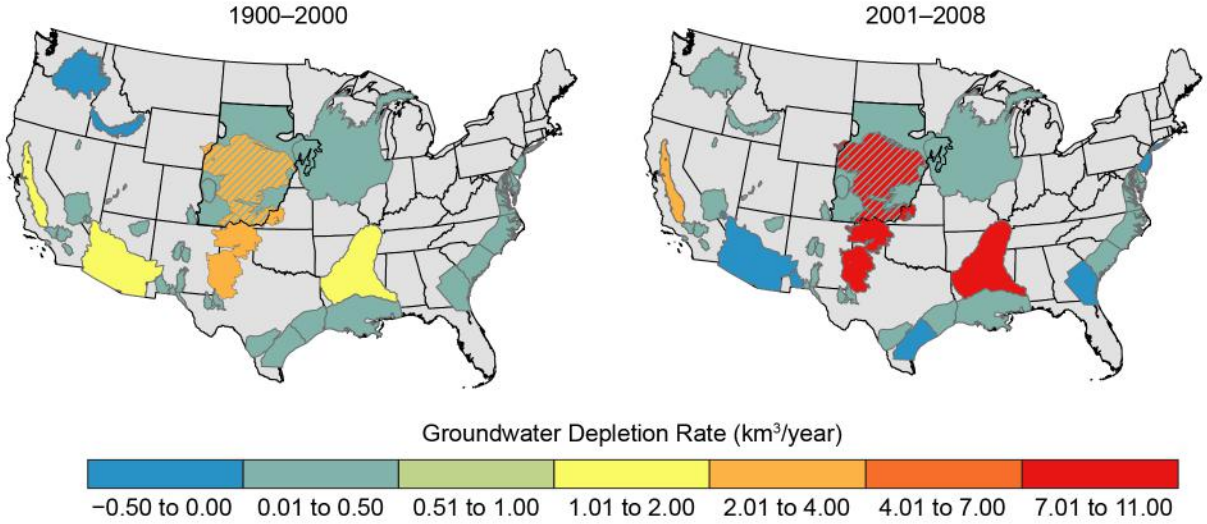
Executive Summary

Ensuring a reliable supply of clean freshwater to individuals, communities, and ecosystems, together with effective management of floods and droughts, is the foundation of human and ecological health. The water sector is also central to the economy and contributes significantly to the resilience of many other sectors, including agriculture, energy, urban environments, and industry.

Water systems face considerable risk, even without anticipated future climate changes. Limited surface water storage, as well as a limited ability to make use of long-term drought forecasts and to trade water across uses and basins, has led to a significant depletion of aquifers in many regions in the United States.[1] Across the Nation, much of the critical water and wastewater infrastructure is nearing the end of its useful life. To date, no comprehensive assessment exists of the climate-related vulnerability of U.S. water infrastructure (including dams, levees, aqueducts, sewers, and water and wastewater distribution and treatment systems), the potential resulting damages, or the cost of reconstruction and recovery. Paleoclimate information (reconstructions of past climate derived from ice cores or tree rings) shows that over the last 500 years, North America has experienced pronounced wet/dry regime shifts that sometimes persisted for decades.[2] Because such protracted exposures to extreme floods or droughts in different parts of the country are extraordinary compared to events experienced in the 20th century, they are not yet incorporated in water management principles and practice. Anticipated future climate change will exacerbate this risk in many regions.

A central challenge to water planning and management is learning to plan for plausible future climate conditions that are wider in range than those experienced in the 20th century. Doing so requires approaches that evaluate plans over many possible futures instead of just one, incorporate real-time monitoring and forecast products to better manage extremes when they occur, and update policies and engineering principles with the best available geoscience-based understanding of planetary change. While this represents a break from historical practice, recent examples of adaptation responses undertaken by large water management agencies, including major metropolitan water utilities and the U.S. Army Corps of Engineers, are promising.

Depletion of Groundwater in Major U.S. Regional Aquifers



(left) Groundwater supplies have been decreasing in the major regional aquifers of the United States over the last century (1900–2000). (right) This decline has accelerated recently (2001–2008) due to persistent droughts in many regions and the lack of adequate surface water storage to meet demands. This decline in groundwater compromises the ability to meet water needs during future droughts and impacts the functioning of groundwater dependent ecosystems (e.g., Kløve et al. 2014[3]).The values shown are net volumetric rates of groundwater depletion (km^3 per year) averaged over each aquifer. Subareas of an aquifer may deplete at faster rates or may be actually recovering. Hatching in the figure represents where the High Plains Aquifer overlies the deep, confined Dakota Aquifer. *From Figure 3.2 (Source: adapted from Konikow 2015.[4] Reprinted from Groundwater with permission of the National Groundwater Association. ©2015).*

State of the Sector

Water security in the United States is increasingly in jeopardy. Ensuring a reliable supply of clean freshwater to communities, agriculture, and ecosystems, together with effective management of floods and droughts, is the foundation of human and ecological health. The water sector is also central to the economy, contributing significantly to the resilience of many other sectors, including agriculture (Ch. 10: Ag & Rural, KM 2 and 4), energy (Ch. 4: Energy), urban environments (Ch. 11: Urban), and industry. The health and productivity of natural aquatic and wetland ecosystems are also closely linked to the water sector (Ch. 7: Ecosystems, KM 1).

Changes in the frequency and intensity of climate extremes relative to the 20th century[5,6] and deteriorating water infrastructure are contributing to declining community and ecosystem resilience. Climate change is a major driver of changes in the frequency, duration, and geographic distribution of severe storms, floods, and droughts (Ch. 2: Climate). In addition, paleoclimate information (reconstructions of past climate derived from ice cores or tree rings) shows that over the last 500 years, North America has experienced pronounced wet/dry regime shifts that sometimes persisted for decades.[2] These shifts led to protracted exposures to extreme floods or droughts in different parts of the country that are extraordinary compared to events experienced in the 20th century. Operational principles for engineering, design, insurance programs, water quality regulations, and water allocation generally have not factored in these longer-term perspectives on historical climate variability or projections of future climate change.[7,8] While there has been much discussion on the need for climate adaptation, the design and implementation of processes that consider near- and long-term information on a changing climate are still nascent.[9,10,11]

Water systems face considerable risk even without anticipated future climate changes. Gains in water-use efficiency over the last 30 years have resulted in total U.S. water consumption staying relatively constant.[12] Gains in efficiency are most evident in urban centers.[13] However, limited surface water storage and a limited ability to make use of long-term drought forecasts and to trade water across uses and basins have led to the significant depletion of aquifers in many regions of the United States.[1] Aging and deteriorating dams and levees[14] also represent an increasing hazard when exposed to extreme or, in some cases, even moderate rainfall. Several recent heavy rainfall events have led to dam, levee, or critical infrastructure failures, including the Oroville emergency spillway in California in 2017,[15] Missouri River levees in 2017, 50 dams in South Carolina in October 2015[16] and 25 more dams in the state in October 2016,[17] and New Orleans levees in 2005 and 2015.[18] The national exposure to this risk has not yet been fully assessed.

Regional Summary

Every region of the United States is affected by water sector sensitivities to weather- and climate-related events (see Figure 3.1). Recent examples are summarized below:

- *Northern and Southern Great Plains*: Future changes in precipitation and the potential for more extreme rainfall events will exacerbate water-related challenges in the Northern Great Plains (Ch. 22: N. Great Plains, KM 1). Extreme precipitation and rising sea levels associated with climate change make the built environment in the Southern Great Plains increasingly vulnerable to disruption, particularly as infrastructure ages and deteriorates (Ch. 23: S. Great Plains, KM 2). Flooding on the Mississippi and Missouri Rivers in May 2011 caused an estimated

$5.7 billion in damages (in 2018 dollars).[19] One year later, drought conditions in 2012 led to record low flows on the Mississippi, disrupting river navigation and agriculture and resulting in widespread harvest failures for corn, sorghum, soybean, and other crops (e.g., Ziska et al. 2016[20]). The nationwide total damage from the 2012 drought is estimated at $33 billion (in 2018 dollars).[19]

- *Northeast and Southeast:* Much of the water infrastructure in the Northeast is nearing the end of its planned life expectancy. Disruptions to infrastructure are already occurring and will likely become more common with a changing climate (Ch. 18: Northeast, KM 3). Hurricane Irene (2011) and Superstorm Sandy (2012) highlighted the inadequacy of deteriorating urban infrastructure, including combined sewers, for managing current and future storm events.[19] In the Southeast, the combined effects of extreme rainfall events and rising sea level are increasing flood frequencies, making coastal and low-lying regions highly vulnerable to climate change impacts (Ch. 8: Coastal, KM 1; Ch. 19: Southeast, KM 2). In South Carolina in 2015, locally extreme rainfall exceeding 20 inches over 3 days[19] caused widespread damage, including the failure of 49 state-regulated dams, one federally regulated dam, two sections of the levee adjacent to the Columbia Canal, and many unregulated dams.[16] In Louisiana in 2016, a severe large-scale storm with record atmospheric moisture dropped nearly 20 inches of rain in 72 hours, triggering widespread flooding that damaged at least 60,000 homes and led to 13 deaths.[21]

- *Midwest:* Storm water management systems and other critical infrastructure in the Midwest are already experiencing impacts from changing precipitation patterns and elevated flood risks (Ch. 21: Midwest, KM 5). In addition, harmful algal blooms (HABs) in western Lake Erie have been steadily increasing over the past decade.[22] Warmer temperatures and heavy precipitation associated with climate change contribute to the development of HABs.[23,24] Harmful algal blooms can introduce cyanobacteria into recreational and drinking water sources, resulting in restrictions on access and use. In 2014 in Toledo, Ohio, half a million people were warned to avoid drinking the water due to toxins overwhelming a water treatment plant in Lake Erie's western basin as a result of a harmful bloom. Conditions that encourage cyanobacteria growth, such as higher water temperatures, increased runoff, and nutrient-rich habitats, are projected to increase in the Midwest (Ch. 21: Midwest).

- *Northwest and Alaska:* Pacific salmon populations in the Northwest are being affected by climate stressors, including low snowpack (such as in 2015), decreasing summer streamflow,[25,26] habitat loss through increasing storm intensity and flooding,[27,28] physiological and behavioral sensitivity, and increasing mortality due to warmer stream and ocean temperatures.[29] Salmon are a cultural and ecological keystone species in this region. Salmon loss is a particular threat to the cultural identities and economies of Indigenous communities (Ch. 24: Northwest, KM 2; Ch. 15: Tribes). In Alaska, residents, communities, and their infrastructure also continue to be affected by flooding and erosion of coastal and river areas, resulting from changes in sea ice (Ch. 26: Alaska, KM 2).

- *Southwest:* Water supplies for people and nature in the Southwest are decreasing during droughts due in part to human-caused climate change. Intensifying droughts, increasing heavy downpours, and reduced snowpack are combining with increasing water demands from a growing population, deteriorating infrastructure,

and groundwater depletion to reduce the future reliability of water supplies (Ch. 25: Southwest, KM 1). The 2011–2016 California drought was characterized by low precipitation combined with record high temperatures, leading to significant socioeconomic and environmental impacts.[30,31] Drought risk is being exacerbated by increasing human water use and the depletion of groundwater that serves as a buffer against water scarcity.[30] Rising air temperatures may increase the chance of droughts in the western United States.[31,32] Compounding the impacts of drought in February 2017, heavy, persistent rainfall across northern and central California led to substantial property and infrastructure damage from record flooding, landslides, and erosion.

- *U.S. Caribbean, Hawai'i and U.S.-Affiliated Pacific Islands:* Dependable and safe water supplies for the communities and ecosystems of the U.S. Caribbean, Hawai'i, and the U.S.-Affiliated Pacific Islands are threatened by rising temperatures, sea level rise, saltwater intrusion, and increased risk of extreme drought and flooding (Ch. 20: U.S. Caribbean, KM 1; Ch. 27: Hawai'i & Pacific Islands, KM 1). The U.S. Caribbean is experiencing an increasing frequency of extreme events that threaten life, property, and the economy (Ch. 20: U.S. Caribbean, KM 5). On September 20, 2017, Hurricane Maria struck the U.S. Virgin Islands as a Category 5 storm and then Puerto Rico as a Category 4 storm—just two weeks after Hurricane Irma had struck the Caribbean islands. The storms left devastation in their wake, with the power distribution severely damaged and drinking water and wastewater treatment plants rendered inoperable.[33] Maria's extreme rainfall, up to 37 inches in 48 hours in some places,[34] also caused widespread flooding and mudslides across the islands.

Billion-Dollar Weather and Climate Disaster Events in the United States

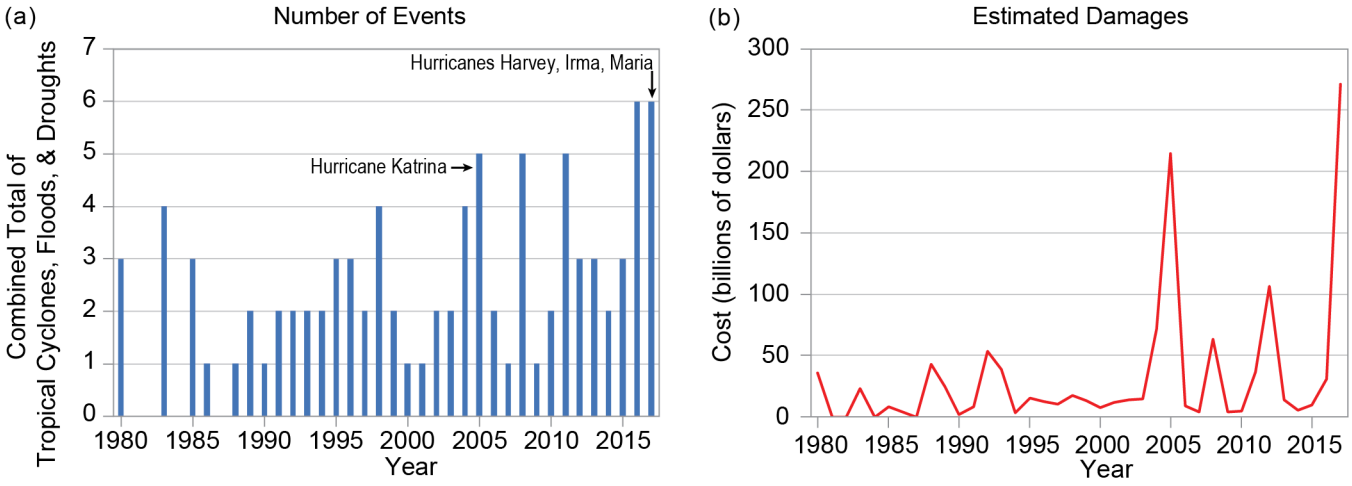


Figure 3.1: The figure shows (a) the total number of water-related billion-dollar disaster events (tropical cyclones, flooding, and droughts combined) each year in the United States and (b) the associated costs (in 2017 dollars, adjusted for inflation). Source: adapted from NOAA NCEI 2018.[19]

Key Message 1

Changes in Water Quantity and Quality

Significant changes in water quantity and quality are evident across the country. These changes, which are expected to persist, present an ongoing risk to coupled human and natural systems and related ecosystem services. Variable precipitation and rising temperature are intensifying droughts, increasing heavy downpours, and reducing snowpack. Reduced snow-to-rain ratios are leading to significant differences between the timing of water supply and demand. Groundwater depletion is exacerbating drought risk. Surface water quality is declining as water temperature increases and more frequent high-intensity rainfall events mobilize pollutants such as sediments and nutrients.

Climate change effects on hydrology, floods, and drought for the United States are discussed in the *Climate Science Special Report*[35,36] and the Third National Climate Assessment.[6] Increasing air temperatures have substantially reduced the fraction of winter precipitation falling as snow, particularly over the western United States.[37,38,39,40,41,42] Warming has resulted in a shift in the timing of snowmelt runoff to earlier in the year.[39,43,44,45,46,47] Glaciers continue to melt in Alaska[25,48] and the western United States (Ch. 1: Overview, Figure 1.2d).[49,50] Shifts in the hydrological regime due to glacier melting will alter stream water volume, water temperature, runoff timing, and aquatic ecosystems in these regions. As temperatures continue to rise, there is a risk of decreased and highly variable water supplies for human use and ecosystem maintenance.[32,51]

Additionally, heavy precipitation events in most parts of the United States have increased in both intensity and frequency since 1901 and are projected to continue to increase over this century under both a lower and higher scenario (RCP4.5 and RCP8.5; see Easterling et al. 2017, Key Finding 2[35]). There are, however, important regional and seasonal differences in projected changes in total precipitation.

Higher temperatures also result in increased human use of water, particularly through increased water demand for agriculture arising from increased evapotranspiration (Ch. 10: Ag & Rural, KM 1).[52,53] In some regions of the United States, water supplies are already stressed by increasing consumption.[12] Continued warming will add to the stress on water supplies and adversely impact water supply reliability in parts of the United States. Over the last 30 years, improvements in water-use efficiency have offset the increasing water needs from population growth, and national water use has remained constant.[12] However, without efforts to increase water-use efficiency in rural and urban areas, increased future demand due to warming could exceed future supply in some locations.[13]

In the United States, groundwater provides more than 40% of the water used for agriculture (irrigation and livestock) and domestic water supplies (Ch. 25: Southwest; Ch. 10: Ag & Rural, KM 1).[1,12] Groundwater use for irrigation has increased substantially since about 1900 and in some areas has exceeded natural aquifer recharge rates.[54] For example, in the High Plains Aquifer, the largest freshwater aquifer in the contiguous United States that supports an important agricultural region,[55] the rate of groundwater withdrawal for irrigation is nearly 10 times the rate of natural recharge, resulting in large groundwater depletions (see Figure 3.2).[56,57,58,59] Groundwater pumping for irrigation is a substantial driver of long-term

trends in groundwater levels in the central United States.[60,61] In many parts of the United States, groundwater is being depleted due to increased pumping during droughts and concentrated demands in urban areas.[1] Increasing air temperatures, insufficient precipitation, and associated increases in irrigation requirements will likely result in greater groundwater depletion in the coming decades.[62] The lack of coordinated management of surface water and groundwater storage limits the Nation's ability to address climate variability. Management of surface water and groundwater storage and water quality are not coordinated across different agencies, leading to inefficient response to changing climate.

Changes in climate and hydrology have direct and cascading effects on water quality.[63,64] Anticipated effects include warming water temperatures in all U.S. regions, which affect ecosystem health (Ch. 7: Ecosystems), and locally variable changes in precipitation and runoff, which affect pollutant transport into and within water bodies.[6,65] These changes pose challenges related to the cost and implications of water treatment, and they present a risk to water supplies, public health, and aquatic ecosystems. Increases in high flow events can increase the delivery of sediment,[66,67,68] nutrients,[69,70,71,72] and microbial pathogens[23,73] to streams, lakes, and estuaries; decreases in low flow volume (such as in the summer) and during periods of drought can impact aquatic life through exposure to high water temperatures and reduced dissolved oxygen.[74,75,76] The risk of harmful algal blooms could increase due to an expanded seasonal window of warm water temperatures and the potential for episodic increases in nutrient loading.[23,24,77] In coastal areas, saltwater intrusion into coastal rivers and aquifers can be exacerbated by sea level rise (or relative sea level rise related to vertical land movement) (Ch. 1: Overview, Figure 1.4), storm surges, and altered freshwater runoff. Saltwater intrusion

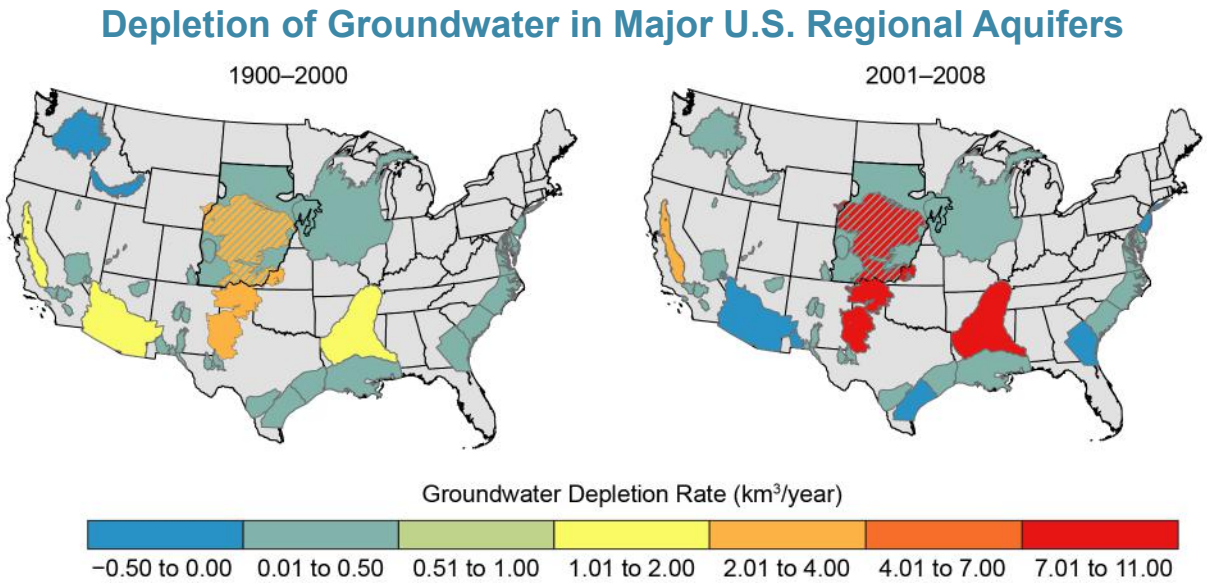


Figure 3.2: (left) Groundwater supplies have been decreasing in the major regional aquifers of the United States over the last century (1900–2000). (right) This decline has accelerated recently (2001–2008) due to persistent droughts in many regions and the lack of adequate surface water storage to meet demands. This decline in groundwater compromises the ability to meet water needs during future droughts and impacts the functioning of groundwater dependent ecosystems (e.g., Kløve et al. 2014[3]).The values shown are net volumetric rates of groundwater depletion (km^3 per year) averaged over each aquifer. Subareas of an aquifer may deplete at faster rates or may be actually recovering. Hatching in the figure represents where the High Plains Aquifer overlies the deep, confined Dakota Aquifer. Source: adapted from Konikow 2015.[4] Reprinted from Groundwater with permission of the National Groundwater Association. © 2015.

could threaten drinking water supplies, infrastructure,[78] and coastal and estuarine ecosystems (Ch. 8: Coastal).[79,80] Indirect impacts on water quality are also possible in response to an increased frequency of forest pest/disease outbreaks, wildfire, and other terrestrial ecosystem changes; land-use changes (for example, agricultural and urban) and water management infrastructure also interact with climate change to impact water quality.

Key Message 2

Deteriorating Water Infrastructure at Risk

Deteriorating water infrastructure compounds the climate risk faced by society. Extreme precipitation events are projected to increase in a warming climate and may lead to more severe floods and greater risk of infrastructure failure in some regions. Infrastructure design, operation, financing principles, and regulatory standards typically do not account for a changing climate. Current risk management does not typically consider the impact of compound extremes (co-occurrence of multiple events) and the risk of cascading infrastructure failure.

Across the Nation, much of the critical water infrastructure is aging and, in some cases, deteriorating or nearing the end of its design life, presenting an increased risk of failure . Estimated reconstruction and maintenance costs aggregated across dams, levees, aqueducts, sewers, and water and wastewater treatment systems total in the trillions of dollars based on a variety of different sources.[14,81,82,83,84,85,86,87] Capital improvement needs for public water systems (which provide safe drinking water) have been estimated at $384 billion for projects necessary from 2011 through 2030.[88] Similarly, capital investment needs for publicly owned wastewater conveyance and treatment facilities, combined sewer overflow correction, and storm water management to address water quality or water quality-related public health problems have been estimated at $271 billion over a 20-year period.[89] More than 15,000 dams in the United States are listed as high risk[85] due to the potential losses that may result if they failed.

Extreme precipitation events are projected to increase in a warming climate and may lead to more severe floods and greater risk of infrastructure failure in some regions.[90] Long-lasting droughts and warm spells can also compromise earth dams and levees as a result of the ground cracking due to drying, a reduction of soil strength, erosion, and subsidence (sinking of land).[91,92] To date, however, there is no comprehensive assessment of the climate-related vulnerability of U.S. water infrastructure, and climate risks to existing infrastructure systems remain unquantified. Tools, case studies, and other information are available that can be adopted into design standards and operational guidelines to account for future climate and/or integrate climate projections into infrastructure design (e.g., EPA 2016, Ragno et al. 2018;[90,93] see also Key Message 3). However, there are no common design standards or operational guidelines that address how infrastructure should be designed and operated in the face of changing climate risk or that even target the range of climate variability seen over the last 500 years.

Procedures for the design, estimation of probability of failure, and risk assessment of infrastructure rely on 10–100 years of past data about flood and rainfall intensity, frequency, and duration (e.g., Vahedifard et al. 2017[15]). This approach assumes that the frequency and severity of extremes do not change significantly over time.[94] However, numerous studies suggest that the severity and frequency of climatic

extremes, such as precipitation and heat waves, have, in fact, been changing.[5,14,25,95,96,97,98,99] These changes present a regionally variable risk of increased frequency and severity of floods and drought.[6,36] In addition, tree ring reconstructions of climate over the past 500 years for the United States illustrate a much wider range of climate variability than does the instrumental record (which begins around 1900).[100,101,102] This historical variability includes wet and dry periods with statistics very different from those of the 20th century. Infrastructure design that uses recent historical data may thus underrepresent the risk seen from the paleo record, even without considering future climate change. Statistical methods have been developed for climate risk and frequency analysis that incorporate observed and/or projected changes in extremes.[90,94,103,104,105] However, these procedures have not yet been incorporated in infrastructure design codes and operational guidelines.

Compound extreme events—the combination of two or more hazard events or climate variables over space and/or time that leads to an extreme impact—have a multiplying effect on the risk to society, the environment, and built infrastructure.[106] Recent examples include the 2016 Louisiana flood, which resulted in simultaneous flooding across a large area (Ch. 19: Southeast, KM 2 and Table 19.1);[21] Superstorm Sandy in 2012, when extreme rainfall coincided with near high tides;[107] and other events combining storm surge and extreme precipitation, such as Hurricane Isaac in 2012 and Hurricane Matthew in 2016. Traditional infrastructure design approaches and risk assessment frameworks often consider these drivers in isolation. For example, current coastal flood risk assessment methods consider changes in terrestrial flooding and ocean flooding separately,[108,109,110,111,112] leading to an underestimation or overestimation of risk in coastal areas.[112] Compound extremes can also increase the risk of cascading infrastructure failure since some infrastructure systems rely on others, and the failure of one system can lead to the failure of interconnected systems, such as water–energy infrastructure (Ch. 4: Energy; Ch. 17: Complex Systems).[113]

Key Message 3

Water Management in a Changing Future

Water management strategies designed in view of an evolving future we can only partially anticipate will help prepare the Nation for water- and climate-related risks of the future. Current water management and planning principles typically do not address risk that changes over time, leaving society exposed to more risk than anticipated. While there are examples of promising approaches to manage climate risk, the gap between research and implementation, especially in view of regulatory and institutional constraints, remains a challenge.

The susceptibility of society to the harmful effects of hydrologic variability and the implications of climate variability and change necessitate a reassessment of the water planning and management principles developed in the 20th century. Significant changes in many key hydrologic design variables (including the quantity and quality of water) and hydrologic extremes are being experienced around the Nation. Paleoclimate analyses and climate projections suggest persistent droughts and wet periods over the continental United States that are longer, cover more area, and are more intense than what was experienced in the 20th century. An evolving future, which can only be partially anticipated, adds to this risk. Furthermore, while hydroclimatic extremes are projected to increase in frequency, accurate predictions of changes in extremes

at a particular location are not yet possible. Instead, climate projections provide a glimpse of possible future conditions and help to scope the plausible range of changes.

A central challenge to water planning and management is learning to plan for plausible future climate conditions that are wider in range than those experienced in the past (see Figure 3.3) (see also Ch. 28: Adaptation, KM 5). Doing so requires approaches that evaluate plans over many possible futures instead of just one, incorporate real-time monitoring and forecast products to better manage extremes when they occur, and update policies and engineering principles with the best available geoscience-based understanding of global change. The challenge is both scientific, in terms of developing and evaluating these approaches, and institutional–political, in terms of updating the regulatory–legal and institutional structures that constrain innovation in water management, planning, and infrastructure design.

One approach is to focus on better managing variability, which is likely the dominant source of operational uncertainty for many water systems.[115] An example of this approach is incorporating monitoring of current conditions and forecasts of near-term future conditions (days to weeks to seasons) in lieu of stationary operating rules based on historical expectations. Forecasts of near-term hydrologic conditions can provide the basis for adaptive reservoir operations, but they require flexible operating rules. New York City, for example, altered existing operational guidelines to implement adaptive reservoir operations based on current hydrologic conditions to better meet new concerns for ecological flow requirements in addition to water supply goals.[116] In another example, the International Joint Commission adopted a new operating plan for Upper Great Lakes water levels; the plan is based on the ability to provide acceptable performance, as defined by stakeholders, over thousands of possible future climates.[117] The plan includes forecast-based operations and a funded adaptive management process linking observatories

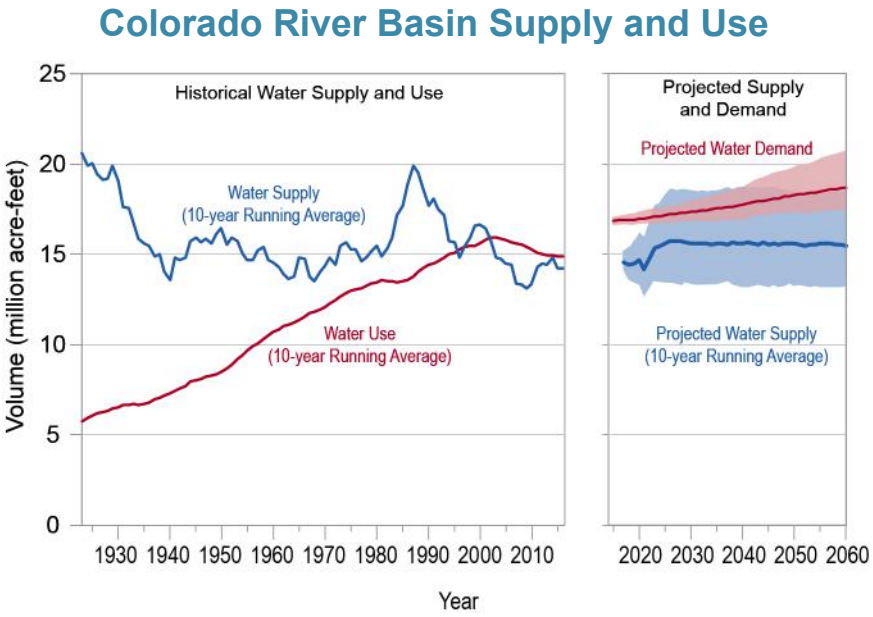


Figure 3.3: The figure shows the Colorado River Basin historical water supply and use, along with projected water supply and demand. The figure illustrates a challenge faced by water managers in many U.S. locations—a potential imbalance between future supply and demand but with considerable long-term variability that is not well understood for the future. For the projections, the dark lines are the median values and the shading represents the 10th to 90th percentile range. Source: adapted from U.S. Bureau of Reclamation 2012.[114]

and information systems to water-release decisions to address unanticipated change.[118] In addition, updating operations and optimizing for changing conditions as they occur provide additional operating flexibility for water supply, flood risk reduction, and hydropower reservoirs.[119,120,121] Finally, financial instruments and water trading provide avenues for managing the effects of variability on water competition, especially between urban water supply and agricultural water use.[122,123,124]

Better management of variability does not eliminate the need for long-term planning that responds to plausible climate changes (see Figure 3.3). Major water utilities provide examples of planning that focus on identifying and managing vulnerabilities to a wide range of uncertain future conditions, rather than evaluating performance for a single future.[125] For example, Tampa Bay Water employed 1,000 realizations of future demand and future supply to evaluate their preparedness for future conditions.[126] Alternatively, Denver Water used a small set of carefully selected future climate and socioeconomic development scenarios to explore possible future vulnerabilities.[125] The World Bank published a set of specific guidelines for implementing such robustness-based approaches in water investment evaluation.[127] As described in Key Message 2, the nature of hydrologic extremes and their rarity complicate the detection of meaningful trends in flood risk,[128] while traditional trend detection methods may lead to missed trends and underpreparation.[129] In response to these challenges, the U.S. Army Corps of Engineers is exploring robustness to a wide range of trends and expected regret as metrics for evaluating flood management strategies,[130,131] including the increased incorporation of natural infrastructure.[132]

Actions taken by communities and the managers of water systems of all sizes can help prepare the Nation for the water-related risks of climate variability and change. The risks associated with a changing climate are compounded by inadequate attention to the state of water infrastructure and insufficient maintenance. Developing new water management and planning approaches may require updating the regulatory, legal, and institutional structures that constrain innovation in water management, community planning, and infrastructure design.[133,134] Furthermore, adequate maintenance and sufficient funding to monitor, maintain, and adapt water policy and infrastructure would help overcome many of these challenges. Continued collaboration on transboundary watershed coordination and agreements on both surface water and groundwater with Canada and Mexico are among the actions that could facilitate more sustainable binational water management practices.

Developing and implementing new approaches pose special challenges for smaller, rural, and other communities with limited financial and technical resources. The development and adoption of new approaches can be facilitated by assessments that compare the effectiveness of new management and planning approaches across regions; greater exchange of emerging expertise among water managers; and better conveyance of the underlying climate and water science to communities, managers, and other decision-makers.[135,136]

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Traceable Accounts

Process Description

Chapter authors were selected based on criteria, agreed on by the chapter lead and coordinating lead authors, that included a primary expertise in water sciences and management, knowledge of climate science and assessment of climate change impacts on water resources, and knowledge of climate change adaptation theory and practice in the water sector.

The chapter was developed through technical discussions and expert deliberation among chapter authors, federal coordinating lead authors, and staff from the U.S. Global Change Research Program (USGCRP). Future climate change impacts on hydrology, floods, and drought for the United States have been discussed in the Third National Climate Assessment[6] and in the USGCRP's *Climate Science Special Report*.[35,36] Accordingly, emphasis here is on vulnerability and the risk to water infrastructure and management presented by climate variability and change, including interactions with existing patterns of water use and development and other factors affecting climate risk. The scope of the chapter is limited to inland freshwater systems; ocean and coastal systems are discussed in their respective chapters in this report.

Key Message 1

Changes in Water Quantity and Quality

Significant changes in water quantity and quality are evident across the country. These changes, which are expected to persist, present an ongoing risk to coupled human and natural systems and related ecosystem services (*high confidence*). Variable precipitation and rising temperature are intensifying droughts (*high confidence*), increasing heavy downpours (*high confidence*), and reducing snowpack (*medium confidence*). Reduced snow-to-rain ratios are leading to significant differences between the timing of water supply and demand (*medium confidence*). Groundwater depletion is exacerbating drought risk (*high confidence*). Surface water quality is declining as water temperature increases (*high confidence*) and more frequent high-intensity rainfall events mobilize pollutants such as sediments and nutrients (*medium confidence*).

Description of evidence base

Increasing air temperatures have substantially reduced the fraction of winter precipitation occurring as snow, particularly over the western United States,[37,38,39,40,41,42,137] and warming has resulted in a shift in the timing of snowmelt runoff to earlier in the year.[39,43,44,45,46]

As reported in the *Climate Science Special Report* and summarized in Chapter 2: Climate, average annual temperature over the contiguous United States has increased by 1.2°F (0.7°C) for the period 1986–2016 relative to 1901–1960, and by 1.8°F (1.0°C) based on a linear regression for the period 1895–2016. Surface and satellite data are consistent in their depiction of rapid warming since 1979. Paleo-temperature evidence shows that recent decades are the warmest of the past 1,500 years. Additionally, contiguous U.S. average annual temperature is projected to rise. Increases of about 2.5°F (1.4°C) are projected for the next few decades in all emission scenarios, implying that recent record-setting years may be common in the near future. Much larger rises are projected by late

century: 2.8°–7.3°F (1.6°–4.1°C) in a lower scenario (RCP4.5) and 5.8°–11.9°F (3.2°–6.6°C) in a higher scenario (RCP8.5).

Annual precipitation has decreased in much of the West, Southwest, and Southeast and increased in most of the Northern and Southern Great Plains, Midwest, and Northeast. There are important regional differences in trends, with the largest increases occurring in the northeastern United States. In particular, mesoscale convective systems (organized clusters of thunderstorms)—the main mechanism for warm season precipitation in the central part of the United States—have increased in occurrence and precipitation amounts since 1979 (see Easterling et al. 2017, Key Finding 1[35]).

Heavy precipitation events in most parts of the United States have increased in both intensity and frequency since 1901 (see Easterling et al. 2017, Key Finding 2[35]) and are projected to continue to increase over this century. There are, however, important regional and seasonal differences in projected changes in total precipitation: the northern United States, including Alaska, is projected to receive more precipitation in the winter and spring, and parts of the southwestern United States are projected to receive less precipitation in the winter and spring (see Easterling et al. 2017, Key Finding 3[35]).

Projections indicate large declines in snowpack in the western United States and shifts to more precipitation falling as rain rather than snow in the cold season in many parts of the central and eastern United States (see Easterling et al. 2017, Key Finding 4[35]).

The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures (see Wehner et al. 2017, Key Finding 2[36]).

Future decreases in surface (top 10 cm) soil moisture from anthropogenic forcing over most of the United States are likely as the climate warms under higher scenarios (see Wehner et al. 2017, Key Finding 3[36]). Substantial reductions in western U.S. winter and spring snowpack are projected as the climate warms. Earlier spring melt and reduced snow water equivalent have been formally attributed to human-induced warming and will very likely be exacerbated as the climate continues to warm. Under higher scenarios, and assuming no change to current water resources management, chronic, long-duration hydrological drought is increasingly possible by the end of this century (see Wehner et al. 2017, Key Finding 4[36]).

Even though national water withdrawal has remained steady irrespective of population growth,[12] there is a significant spatiotemporal variability in water withdrawal (for example, a higher rate over the South) and water-use efficiency across the United States.[13] Siebert et al. 2010[54] reported that irrigation use of groundwater has increased substantially over the past century and that groundwater use for irrigation in some areas has exceeded natural aquifer recharge rates.

Changes in air temperature and precipitation affect water quality in predictable ways. Attribution of water quality changes to climate change, however, is complicated by the multiple cascading, cumulative effects of climate change, land use, and other anthropogenic stressors on water quality. There has been a widespread increase in water temperatures across the United States.[74,138]

These trends are expected to continue in the future, with increased water temperatures likely across the country.[76] Runoff from more frequent and intense precipitation events can increase the risk of pollutant loading as nutrients,[69,70,71] sediment,[66,67,68] and pathogens[23,73] are transported from upland sources to water bodies. Pollutant loading is also strongly influenced by local watershed conditions (for example, land use, vegetative ground cover, pollutant sources). Increases in summer–fall water temperatures, excess nutrient loading events (driven by heavy precipitation events), and longer dry periods (associated with calm, quiescent water conditions) can expand the seasonal window for cyanobacteria and present an increased risk of bloom events.[23,77]

Figure 3.2 shows net, average volumetric rates of groundwater depletion (km^3/year) in 40 assessed aquifer systems or subareas in the contiguous 48 states.[4] Variation in rates of depletion in time and space within aquifers occurs but is not shown. For example, in the Nebraska part of the northern High Plains, small water-table rises occurred in parts of this area, and the net depletion was negligible. In contrast, in the Texas part of the southern High Plains, development of groundwater resources was more extensive, and the depletion rate averaged 1.6 km^3/year.[4]

Major uncertainties

There is high uncertainty associated with projected scenarios, as they include many future decisions and actions that remain unknown. There also is high uncertainty with estimates of precipitation; this uncertainty is reflected in the wide range of climate model estimates of future precipitation. In contrast, because climate model simulations generally agree on the direction and general magnitude of future changes in temperature (given specific emission scenarios), there is a medium level of uncertainty associated with temperature projections. Overall, changes in land use are associated with a medium level of uncertainty. Even though there is low uncertainty regarding the expansion of urban areas, there is greater uncertainty regarding changes in agricultural land use. A medium level of uncertainty for water supply reflects a combination of high uncertainty in streamflow and low uncertainty in water demand. Uncertainty in water demand is low because of adaptation and increased water-use efficiency and because of water storage in reservoirs. Water storage capacity also reduces uncertainty in future groundwater conditions. Water temperature changes are relatively well understood, but other changes in water quality, particularly pollutant loads (such as nutrients, sediment, and pathogens), are associated with high uncertainty due to a combination of uncertain land-use changes and high uncertainty in streamflow and hydrologic processes.

Description of confidence and likelihood

Increasing temperature is *highly likely* to result in early snowmelt and increased consumptive use. Uncertainty in precipitation and emission scenarios leads to *low confidence* in predicting water availability and the associated quality arising from changes in land-use scenarios. However, surface water and groundwater storage ensures *medium confidence* in water quantity and quality reliability, but spatial disparity in water efficiency could be better addressed through increased investment in water infrastructure for system maintenance.

Key Message 2

Deteriorating Water Infrastructure at Risk

Deteriorating water infrastructure compounds the climate risk faced by society (*high confidence*). Extreme precipitation events are projected to increase in a warming climate (*high confidence*) and may lead to more severe floods and greater risk of infrastructure failure in some regions (*medium confidence*). Infrastructure design, operation, financing principles, and regulatory standards typically do not account for a changing climate (*high confidence*). Current risk management does not typically consider the impact of compound extremes (co-occurrence of multiple events) and the risk of cascading infrastructure failure (*high confidence*).

Description of evidence base

Heavy precipitation events in most parts of the United States have increased in both intensity and frequency since about 1900 and are projected to continue to increase over this century, with important regional differences (Ch. 2: Climate).[35,97] Detectable changes in some classes of flood frequency have occurred in parts of the United States and are a mix of increases and decreases (Ch. 2: Climate).[6,139] However, formal attribution approaches have not established a significant connection of increased riverine flooding to human-induced climate change, and the timing of any emergence of a future detectable anthropogenic change in flooding is unclear (Ch. 2: Climate). There is considerable variation in the nature and direction of projected streamflow changes in U.S. rivers (Ch. 2: Climate).[6,140]

Infrastructure systems are typically sized to cope with extreme events expected to occur on average within a certain period of time in the future (for example, 25, 50, or 100 years), based on historical observations.[141] There is substantial concern about the impacts of future changes in extremes on the existing infrastructure. However, the existing operational design and risk assessment frameworks (for example, rainfall intensity–duration–frequency, or IDF, curves and flood frequency curves) are based on the notion of time invariance (stationarity) in extremes.[109,110]

Variability in sea surface temperatures influences atmospheric circulation and subsequently affects the occurrence of regional wet and dry periods in the United States.[142,143,144,145,146] Reconstructed streamflow data capture the extreme dry/wet periods beyond the instrumental record, but a limited literature has considered their application for water management.[147,148]

A number of models have been developed to incorporate the observed and/or projected changes in extremes in frequency analysis and risk assessment.[94,103,104,105,149,150,151,152] The appropriateness of a fixed return period for IDF curves or for flood/drought frequency analysis is also questioned in the literature.[7,14,134,153] This chapter has not evaluated the existing methods in the literature that account for temporal changes in extremes, and the issue warrants more investigation in the future.

Previous studies show that compound extreme events can have a multiplier effect on the risks to society, the environment, and built infrastructure.[112,154] Current design frameworks ignore this issue and mainly rely on one variable at a time.[92,154,155] For example, coastal flood risk assessment is primarily based on univariate methods that consider changes in terrestrial flooding and ocean

flooding separately.[108,109,111] Few studies have offered frameworks for considering multiple hazards for the design and risk assessment of infrastructure.[112,154] Expected changes in the frequency of extreme events and their compounding effects can have significant consequences for existing infrastructure systems.

Major uncertainties

There are high uncertainties in future floods because of uncertainties in future long-term regional/local precipitation and uncertain changes in land use/land cover, water management, and other non-climatic factors that will interact with climate change to affect floods. There also are high uncertainties in future water supply estimates because of uncertainties in future precipitation. Drought increase due to combined precipitation and temperature change has a moderate uncertainty.

Description of confidence and likelihood

There is *high confidence* in the presence of a strong relationship between precipitation and temperature, indicating that changes in one will likely alter the statistics of the other and hence the likelihood of occurrence of extremes. The aging nature of the Nation's water infrastructure is well documented. Not all aging infrastructure is deteriorating, however, and many aging projects are operating robustly under changing conditions. Unfortunately, no national assessment of deteriorating infrastructure or the fragility of infrastructure relative to aging exists. For example, the U.S. Army Corps of Engineers (USACE) has assessed how climate change projections with bias correction compare with the nominal design levels of USACE dams; however, this represents only a fraction of the Nation's 88,000 dams. While age may be an imperfect proxy for deterioration, it is used here to call attention to the general concern that many elements of the Nation's water infrastructure are likely not optimized to address changing climate conditions. There is *high confidence* that deteriorating water infrastructure (dams, levees, aqueducts, sewers, and water and wastewater treatment and distribution systems) compounds the climate risk faced by society.

Studies show that compound extreme events will likely have a multiplier effect on the risk to society, the environment, and built infrastructure. Sea level rise is expected to increase in a warming climate. Sea level rise adds to the height of future storm tides, reduces pressure gradients that are important for transporting fluvial water to the ocean, and enables greater upstream tide/wave propagation and coastal flooding.

There is *high confidence* in the existence of the interannual and decadal cycles but *medium confidence* in the ability to accurately simulate the joint effects of these cycles and anthropogenic climate change for water impacts.

Currently, coastal flood risk assessment is primarily based on univariate methods that consider changes in terrestrial flooding and ocean flooding separately, which may not reliably estimate the probability of interrelated compound extreme events. The expected changes in the frequency of extreme events and their compounding effects will likely have significant consequences for existing infrastructure systems. Because of the uncertainties in future precipitation and how extreme events compound each other, there is *medium confidence* in the effects of compound extremes (multiple extreme events) on infrastructure failure.

Key Message 3

Water Management in a Changing Future

Water management strategies designed in view of an evolving future we can only partially anticipate will help prepare the Nation for water- and climate-related risks of the future (*medium confidence*). Current water management and planning principles typically do not address risk that changes over time, leaving society exposed to more risk than anticipated (*medium confidence*). While there are examples of promising approaches to manage climate risk, the gap between research and implementation, especially in view of regulatory and institutional constraints, remains a challenge.

Description of evidence base

There is wide documentation in the scientific literature that water management practice and engineering design use the observed historical record as a guide to future expectations. This implies that significant departures from those expectations would pose greater-than-anticipated risks, and scenario analyses have demonstrated this to be the case, particularly in studies of large water supply systems. In particular, the *Climate Science Special Report*[5] notes the potential for increased clustering (for example, heat waves and drought) or sequences of extremes and rapid transitions in climate. There is a growing literature that documents the use of robustness-based planning approaches, especially for water supply planning but also for coastal planning. These approaches provide promising methodologies for addressing climate change in water planning, although their complexity and cost—and limited planning resources—may be impediments to wide-scale adoption.

The literature also provides examples of some more innovative approaches applied to managing risks in an adaptive manner, including updating reservoir operations,[116,126,156] employing financial instruments for risk transfer or financial risk management,[123,157] and the use of adaptive management.[117] However, the lack of broader-scale adoption and wider demonstration prevents more conclusive statements regarding the general utility of these approaches at this time.[120]

Major uncertainties

The key uncertainty in assessing the current state of preparation of the Nation's water infrastructure and management for climate change is the lack of public data collected about key performance and risk parameters. This includes the state of water infrastructure, including dams, levees, distribution systems, storm water collection, and water and wastewater treatment systems. For some of these systems, current performance information may be available, but there is little knowledge of what future performance limitations may be. Furthermore, much of this information is not publicly available, although it may be collected by the many local and state agencies that operate these infrastructure systems. A large number of case studies have illustrated that observed and projected changes in climate could place systems at risk in ways that exceed current expectations.

Description of confidence and likelihood

The Key Message is stated with *medium confidence* due to the limited assessment that has been performed on water infrastructure systems and management regimes, and due to the nascent and limited assessment of proposed adaptive responses.

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4 Energy Supply, Delivery, and Demand

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4 Energy Supply, Delivery, and Demand

Linemen working to restore power in Puerto Rico after Hurricane Maria in 2017

Key Message 1

Nationwide Impacts on Energy

The Nation's energy system is already affected by extreme weather events, and due to climate change, it is projected to be increasingly threatened by more frequent and longer-lasting power outages affecting critical energy infrastructure and creating fuel availability and demand imbalances. The reliability, security, and resilience of the energy system underpin virtually every sector of the U.S. economy. Cascading impacts on other critical sectors could affect economic and national security.

Key Message 2

Changes in Energy System Affect Vulnerabilities

Changes in energy technologies, markets, and policies are affecting the energy system's vulnerabilities to climate change and extreme weather. Some of these changes increase reliability and resilience, while others create additional vulnerabilities. Changes include the following: natural gas is increasingly used as fuel for power plants; renewable resources are becoming increasingly cost competitive with an expanding market share; and a resilient energy supply is increasingly important as telecommunications, transportation, and other critical systems are more interconnected than ever.

Key Message 3

Improving Energy System Resilience

Actions are being taken to enhance energy security, reliability, and resilience with respect to the effects of climate change and extreme weather. This progress occurs through improved data collection, modeling, and analysis to support resilience planning; private and public–private partnerships supporting coordinated action; and both development and deployment of new, innovative energy technologies for adapting energy assets to extreme weather hazards. Although barriers exist, opportunities remain to accelerate the pace, scale, and scope of investments in energy systems resilience.

Executive Summary

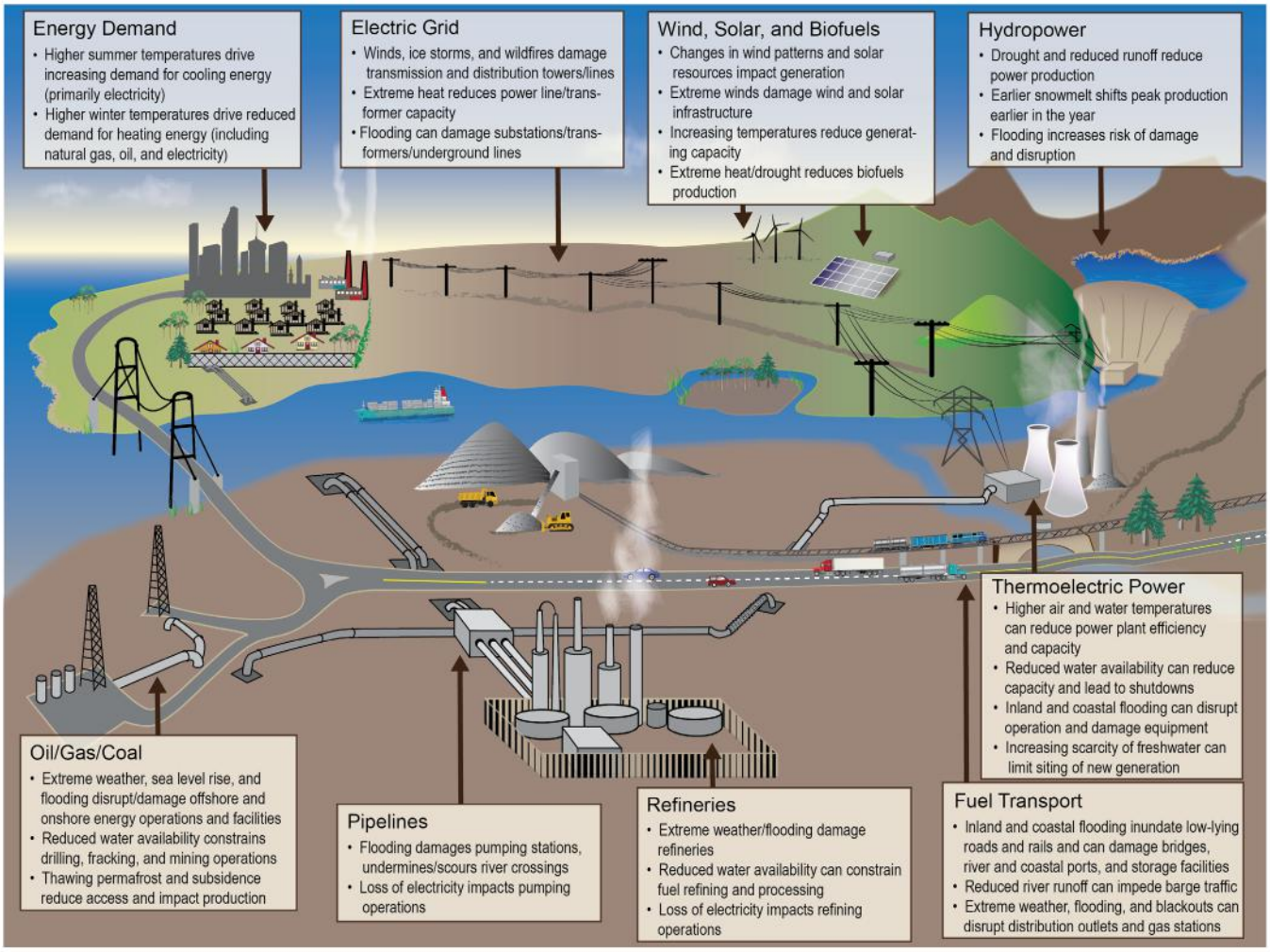
The Nation's economic security is increasingly dependent on an affordable and reliable supply of energy.[1,2] Every sector of the economy depends on energy, from manufacturing to agriculture, banking, healthcare, telecommunications, and transportation. Increasingly, climate change and extreme weather events are affecting the energy system, threatening more frequent and longer-lasting power outages and fuel shortages. Such events can have cascading impacts on other critical sectors, potentially affecting the Nation's economic and national security. At the same time, the energy sector is undergoing substantial policy, market, and technology-driven changes that are projected to affect these vulnerabilities.

The impacts of extreme weather and climate change on energy systems will differ across the United States.[3] Low-lying energy facilities and systems located along inland waters or near the coasts are at elevated risk of flooding from more intense precipitation, rising sea levels, and more intense hurricanes.[4,5,6,7,8] Increases in the severity and frequency of extreme precipitation are projected to affect inland energy infrastructure in every region. Rising temperatures and extreme heat events are projected to reduce the generation capacity of thermoelectric power plants and decrease the efficiency of the transmission grid.[9,10] Rising temperatures are projected to also drive greater use of air conditioning and increase electricity demand, likely resulting in increases in electricity costs.[8,11,12,13,14,15,16,17,18,19] The increase in annual electricity demand across the country for cooling is offset only marginally by the relatively small decline in electricity demand for heating. Extreme cold events, including ice and snow events, can damage power lines and impact fuel supplies.[20] Severe drought, along with changes in evaporation, reductions in mountain snowpack, and shifting mountain snowmelt timing, is projected to reduce hydropower production and threaten oil and gas drilling and refining, as well as thermoelectric power plants that rely on surface water for cooling.[3,21,22,23,24] Drier conditions are projected to increase the risk of wildfires and damage to energy production and generation assets and the power grid.[3,8]

At the same time, the nature of the energy system itself is changing.[1,2,22,25,26,27,28,29,30,31,32,33,34] Low carbon-emitting natural gas generation has displaced coal generation due to the rising production of low-cost, unconventional natural gas, in part supported by federal investment in research and development.[35] In the last 10 years, the share of generation from natural gas increased from 20% to over 30%, while coal has declined from nearly 50% to around 30%.[36] Over this same time, generation from wind and solar has grown from less than 1% to over 5% due to a combination of technological progress, dramatic cost reductions, and federal and state policies.[2,33]

It is possible to address the challenges of a changing climate and energy system, and both industry and governments at the local, state, regional, federal, and tribal levels are taking actions to improve the resilience of the Nation's energy system. These actions include planning and operational measures that seek to anticipate climate impacts and prevent or respond to damages more effectively, as well as hardening measures to protect assets from damage during extreme events.[3,37,38,39,40,41,42] Resilience actions can have co-benefits, such as developing and deploying new innovative energy technologies that increase resilience and reduce emissions. While steps are being taken, an escalation of the pace, scale, and scope of efforts is needed to ensure the safe and reliable provision of energy and to establish a climate-ready energy system to address present and future risks.

Potential Impacts from Extreme Weather and Climate Change



Extreme weather and climate change can potentially impact all components of the Nation's energy system, from fuel (petroleum, coal, and natural gas) production and distribution to electricity generation, transmission, and demand. *From Figure 4.1 (Source: adapted from DOE 2013* [23]*)*.

State of the Sector

The Nation's economic security is increasingly dependent on an affordable and reliable supply of energy. Every sector of the economy depends on energy, from manufacturing to agriculture, banking, healthcare, telecommunications, and transportation.[2] Increasingly, climate change and extreme weather events are affecting the energy system (including all components related to the production, conversion, delivery, and use of energy), threatening more frequent and longer-lasting power outages and fuel shortages.[3] Such events can have cascading impacts on other critical sectors[43,44] and potentially affect the Nation's economic and national security (Ch. 17: Complex Systems). At the same time, the energy sector is undergoing substantial policy-, market-, and technology-driven changes.[2,31] Natural gas and renewable resources are moving to the forefront as energy sources and energy efficiency efforts continue to expand, forcing changes to the design and operation of the Nation's gas infrastructure and electrical grid. Beyond these changes, deliberate actions are being taken to enhance energy security, reliability, and resilience with respect to the effects of climate change through integrated planning, innovative energy technologies, and public–private partnerships;[1,2,31,45] however, much work remains to establish a climate-ready energy system that addresses present and future risks.

Regional Summary

Energy systems and the impacts of climate change differ across the United States, but all regions will be affected by a changing climate. The petroleum, natural gas, and electrical infrastructure along the East and Gulf Coasts are at increased risk of damage from rising sea levels and hurricanes of greater intensity (Ch. 18: Northeast, KM 3; Ch. 19: Southeast, KM 1 and 2). This vulnerable infrastructure serves other parts of the country, so regional disruptions are projected to have national implications. Hawai'i and the U.S. Caribbean (Ch. 27: Hawai'i & Pacific Islands, KM 3; Ch. 20: U.S. Caribbean, KM 3 and 5) are especially vulnerable to sea level rise and extreme weather, as they rely on imports of petroleum through coastal infrastructure, ports, and storage facilities. Oil and gas operations in Alaska are vulnerable to thawing permafrost, which, together with sea level rise and dwindling protective sea ice, is projected to damage existing infrastructure and restrict seasonal access; however, a longer ice-free season may enhance offshore energy exploration and transport (Ch. 26: Alaska, KM 5). More frequent and intense extreme precipitation events are projected to increase the risk of floods for coastal and inland energy infrastructure, especially in the Northeast and Midwest (Ch. 18: Northeast, KM 1 and 3; Ch. 21: Midwest, KM 5). Temperatures are rising in all regions, and these increases are expected to drive greater use of air conditioning. The increase in annual electricity demand across the country for cooling is offset only marginally by the relatively small decline in heating demand that is met with electric power.[11] In addition, higher temperatures reduce the thermal efficiency and generating capacity of thermoelectric power plants and reduce the efficiency and current-carrying capacity of transmission and distribution lines.

Energy systems in the Northwest and Southwest are likely to experience the most severe impacts of changing water availability, as reductions in mountain snowpack and shifts in snowmelt timing affect hydropower production (Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM 5). Drought will likely threaten fuel production, such as fracking for natural gas and shale oil; enhanced oil recovery in the Northeast, Midwest, Southwest, and Northern and Southern Great Plains; oil refining; and thermoelectric power generation that relies

on surface water for cooling. In the Midwest, Northern Great Plains, and Southern Great Plains, higher temperatures and reduced soil moisture will likely make it more difficult to grow biofuel crops and impact the availability of wood and wood waste products for heating, fuel production, and electricity generation (Ch. 22: N. Great Plains, KM 4; Ch. 23: S. Great Plains, KM 1 and 2).

Key Message 1

Nationwide Impacts on Energy

The Nation's energy system is already affected by extreme weather events, and due to climate change, it is projected to be increasingly threatened by more frequent and longer-lasting power outages affecting critical energy infrastructure and creating fuel availability and demand imbalances. The reliability, security, and resilience of the energy system underpin virtually every sector of the U.S. economy. Cascading impacts on other critical sectors could affect economic and national security.

The principal contributor to power outages, and their associated costs, in the United States is extreme weather.[2,8,46] Extreme weather includes high winds, thunderstorms, hurricanes, heat waves, intense cold periods, intense snow events and ice storms, and extreme rainfall. Such events can interrupt energy generation, damage energy resources and infrastructure, and interfere with fuel production and distribution systems, causing fuel and electricity shortages or price spikes (Figure 4.1). Many extreme weather impacts are expected to continue growing in frequency and severity over the coming century,[8] affecting all elements of the Nation's complex energy supply system and reinforcing the energy supply-and-use findings of prior National Climate Assessments.[9]

Extreme weather can damage energy assets—a broad suite of equipment used in the production, generation, transmission, and distribution of energy—and cause widespread energy disruption that can take weeks to fully resolve, at sizeable economic costs.[2,3] High winds threaten damage to electricity transmission and distribution lines (Box 4.1), buildings, cooling towers, port facilities, and other onshore and offshore structures associated with energy infrastructure and operations.[3] Extreme rainfall (including extreme precipitation events, hurricanes, and atmospheric river events) can lead to flash floods that undermine the foundations of power line and pipeline crossings and inundate common riverbank energy facilities such as power plants, substations, transformers, and refineries.[3] River flooding can also shut down or damage fuel transport infrastructure such as railroads, fuel barge ports, pipelines, and storage facilities.[3]

Box 4.1: Economic Impacts to Electricity Systems

Repairs to electricity generation, transmission, and distribution systems from recent hurricane events are costing billions of dollars. Con Edison and Public Service Electric and Gas invested over $2 billion (in 2014 dollars) in response to Superstorm Sandy.[50,51] An estimate to build back Puerto Rico's electricity systems in response to Hurricanes Irma and Maria is approximately $17 billion (in 2017 dollars).[52]

Coastal flooding threatens much of the Nation's energy infrastructure, especially in regions with highly developed coastlines.[4,5,6] Coastal flooding, including wave action and storm surge (where seawater moves inland, often at levels above typical high tides due to strong winds), can affect gas and electric asset performance, cause asset damage and failure,

Potential Impacts from Extreme Weather and Climate Change

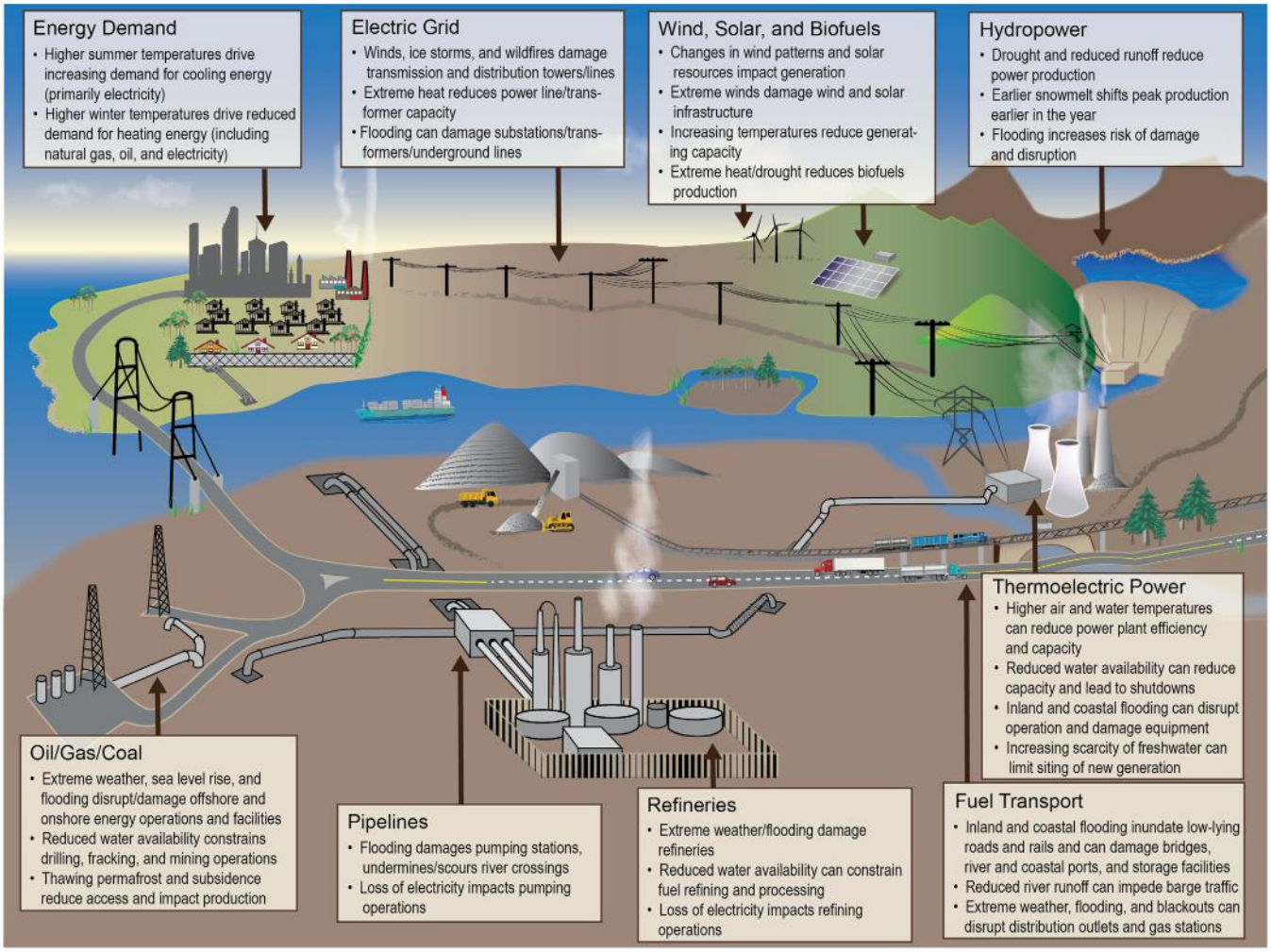


Figure 4.1: Extreme weather and climate change can potentially impact all components of the Nation's energy system, from fuel (petroleum, coal, and natural gas) production and distribution to electricity generation, transmission, and demand. Source: adapted from DOE 2013.[23]

and disrupt energy generation, transmission, and delivery. In addition, flooding can cause large petroleum storage tanks to float, destroying the tanks and potentially creating hazardous spills.[3] Any significant increase in hurricane intensities would greatly exacerbate exposure to storm surge and wind damage.

In the Southeast (Atlantic and Gulf Coasts), power plants and oil refineries are especially vulnerable to flooding. The number of electricity generation facilities in the Southeast potentially exposed to hurricane storm surge is estimated at 69 and 291 for Category 1 and Category 5 storms, respectively.[4] Nationally, a sea level rise of 3.3 feet (1 m; at the high end of the very likely range under a lower scenario [RCP4.5] for 2100) (for more on RCPs, see the Scenario Products section in App. 3)[47] could expose dozens of power plants that are currently out of reach to the risks of a 100-year flood (a flood having a 1% chance of occurring in a given year). This would put an additional cumulative total of 25 gigawatts (GW) of operating or proposed power capacities at risk.[48] In Florida and Delaware, sea level rise of 3.3 feet (1 m) would double the number of vulnerable plants (putting an additional 11 GW and 0.8 GW at risk in the two states, respectively); in Texas, vulnerable capacity would more than

triple (with an additional 2.8 GW at risk).[48] Sea level rise and storm surge already pose a risk to coastal substations; this risk is projected to increase as sea levels continue to rise. For example, in southeastern Florida the number of major substations exposed to flooding from a Category 3 storm could more than double by 2050 and triple by 2070 under the higher scenario (RCP8.5).[49] Under RCP8.5, the projected number of electricity substations in the Gulf of Mexico exposed to storm surge from Category 1 hurricanes could increase by over 30% and nearly 60% by 2030 and 2050, respectively.[1] Increases in baseline sea levels expose many more Gulf Coast refineries to flooding risk during extreme weather events. For example, given a Category 1 hurricane, a sea level rise of less than 1.6 feet (0.5 m)[47] doubles the number of refineries in Texas and Louisiana vulnerable to flooding by 2100 under the lower scenario (RCP4.5).[4]

Rising air and water temperatures and extreme heat events[53,54,55] drive increases in demand for cooling while simultaneously resulting in reduced capacity and increased disruption of power plants and the electric grid, and potentially increasing electricity prices to consumers. Increased demand for cooling will likely also increase energy-related emissions of criteria air pollutants (for example, nitrogen oxide and sulfur dioxide), presenting an additional challenge to meet national ambient air quality standards, which are particularly important in the summer, when warmer temperatures and more direct sunlight can exacerbate the formation of photochemical smog (Ch. 13: Air Quality, KM 1 and 4). Unless other mitigation strategies are implemented, more frequent, severe, and longer-lasting extreme heat events are expected to make blackouts and power disruptions more common, increase the potential for electricity infrastructure to malfunction, and result in increased risks to public health and safety.[2,3,8,15,56]

If greenhouse gas emissions continue unabated (as with the higher scenario [RCP8.5]), rising temperatures are projected to drive up electricity costs and demand. Despite anticipated gains in end use and building and appliance efficiencies, higher temperatures are projected to drive up electricity costs not only by increasing demand but also by reducing the efficiency of power generation and delivery, and by requiring new generation capacity costing residential and commercial ratepayers by some estimates up to $30 billion per year by mid-century.[3,57] By 2040, nationwide, residential and commercial electricity expenditures are projected to increase by 6%–18% under a higher scenario (RCP8.5), 4%–15% under a lower scenario (RCP4.5), and 4%–12% under an even lower scenario (RCP2.6).[13] By the end of the century, an increase in average annual energy expenditures from increased energy demand under the higher scenario is estimated at $32–$87 billion (Figure 4.2; in 2011 dollars for GAO 2017[12] and in 2013 dollars for Rhodium Group LLC 2014, Larsen et al. 2017, Hsiang et al. 2017[16,13,14]). Nationwide, electricity demand is projected to increase by 3%–9% by 2040 under the higher scenario and 2%–7% under the lower scenario.[13] This projection includes the reduction in electricity used for space heating in states with warming winters, the associated decrease in heating degree days, and the increase in electricity demand associated with increases in cooling degree days.

In a lower scenario (RCP4.5), temperatures remain on an upward trajectory that could increase net electricity demand by 1.7%–2.0%.[15] To ensure grid reliability, enough generation and storage capacity must be available to meet the highest peak load demand. Rising temperatures could necessitate the construction

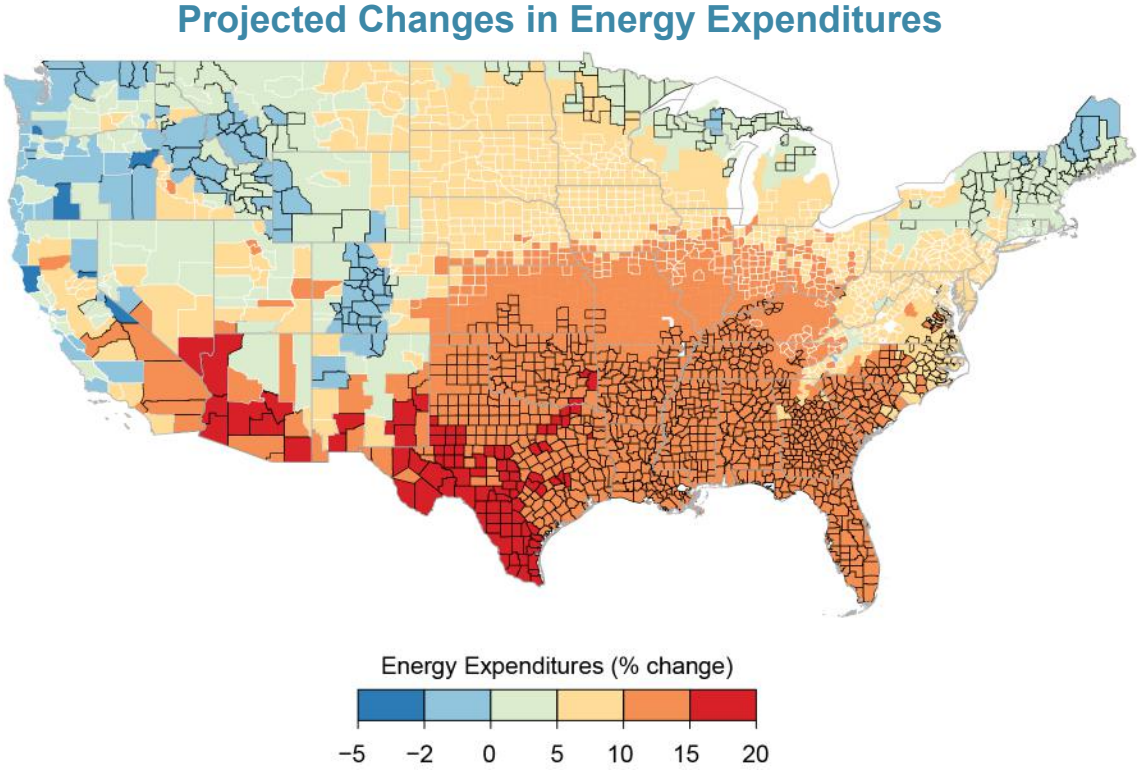


Figure 4.2: This figure shows county-level median projected increases in energy expenditures for average 2080–2099 impacts under the higher scenario (RCP8.5). Impacts are changes relative to no additional change in climate. Color indicates the magnitude of increases in energy expenditures in median projection; outline color indicates level of agreement across model projections (thin white outline, inner 66% of projections disagree in sign; no outline, more than 83% of projections agree in sign; black outline, more than 95% agree in sign; thick gray outline, state borders). Data were unavailable for Alaska, Hawai'i and the U.S.-Affiliated Pacific Islands, and the U.S. Caribbean regions. Source: Hsiang et al. 2017.[14]

of up to 25% more power plant capacity by 2040, compared to a scenario without a warming climate.[13]

Most U.S. power plants, regardless of fuel source (for example, coal, natural gas, nuclear, concentrated solar, and geothermal), rely on a steady supply of water for cooling, and operations are projected to be threatened when water availability decreases or water temperatures increase (Ch. 3: Water; Ch. 17: Complex Systems, Box 17.3).[3] Elevated water temperatures reduce power plant efficiency; in some cases, a plant could have to shut down to comply with discharge temperature regulations designed to avoid damaging aquatic ecosystems.[3] In North America, the output potential of power plants cooled by river water could fall by 7.3% and 13.1% by 2050 under the RCP2.6 and RCP8.5 scenarios, respectively.[21]

A changing climate also threatens hydropower production, especially in western snow-dominated watersheds, where declining mountain snowpack affects river levels (Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM 5). For example, severe, extended drought caused California's hydropower output to decline 59% in 2015 compared to the average annual production over the two prior decades.[22]

Reduced water availability also affects the production and refining of petroleum, natural gas, and biofuels. During droughts, hydraulic fracturing and fuel refining operations will likely need alternative water supplies (such as brackish groundwater) or to shut down temporarily.[3,23,24] Shutdowns and the adoption of emergency measures and backup systems can increase refinery costs, raising product prices for the consumer.[23] Drought can reduce the cultivation of biofuel

feedstocks (Ch. 10: Ag & Rural) and increase the risk of wildfires that threaten transmission lines and other energy infrastructure.[3,8]

Key Message 2

Changes in Energy System Affect Vulnerabilities

Changes in energy technologies, markets, and policies are affecting the energy system's vulnerabilities to climate change and extreme weather. Some of these changes increase reliability and resilience, while others create additional vulnerabilities. Changes include the following: natural gas is increasingly used as fuel for power plants; renewable resources are becoming increasingly cost competitive with an expanding market share; and a resilient energy supply is increasingly important as telecommunications, transportation, and other critical systems are more interconnected than ever.

The energy sector is undergoing a transformation driven by technology, markets, and policies that will change the sector's vulnerability to extreme weather and climate hazards. New drilling technologies and methods are enabling increased natural gas production, lower prices, and greater consumption. For example, in 2016 for the first time, natural gas replaced coal as the leading source of electricity generation in the United States (Figure 4.3).[22,31] In addition, U.S. net imports of petroleum reached a new low (Box 4.2). Likewise, dramatic reductions in the cost of renewable generation sources have led to the rapid growth of solar and wind installations.[32,58] Solar and wind generation in the United States grew by 44% and 19% during 2016, respectively.[25] These changes offer the opportunity to diversify the energy generation portfolio and require planning for operation and reliability of power generation, transmission, and delivery to maximize the positive effects and avoid unintended consequences. For example, natural gas generation generally improves electric system flexibility and reliability, as gas-fired power plants can quickly ramp output up and down,[2] but gas supplies

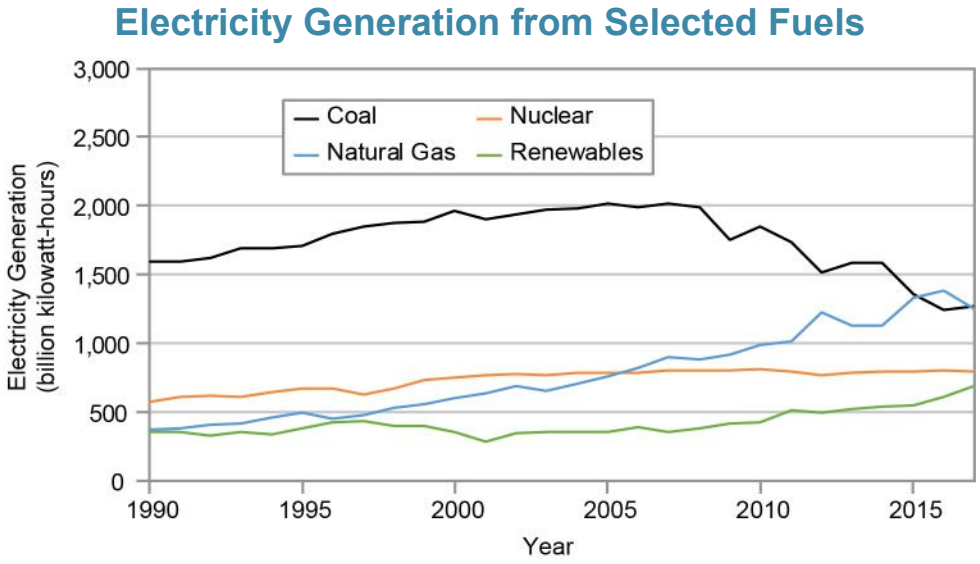


Figure 4.3: This figure shows electric power generation from different fuel sources and technologies. Since 2010, the declining market share from coal has been filled largely by natural gas and, to a lesser extent, renewables. Renewables include: conventional hydroelectric, geothermal, wood, wood waste, biogenic municipal waste, landfill gas, other biomass, solar, and wind power. Source: EIA/AEO 2018.[59]

and midstream infrastructure are vulnerable to disruption as noted previously. The flexible dispatch of gas generation can partially address the intermittency introduced by wide-scale deployment of solar and wind generation, which can be impacted by extreme weather as described earlier.[2] In addition, the growing adoption of energy efficiency programs, demand response programs, transmission capacity increases, and microgrids with energy storage technologies is enhancing system flexibility, reliability, and resilience.[31]

Energy efficiency has been remarkably successful over several decades in helping control energy costs to homes, buildings, and industry, while also contributing to enhanced resilience through reduced energy demand.[2] A number of actions are contributing to the increases in energy efficiency, significant energy savings, and improved resilience, including: the use of tax policy and other financial incentives to lower the cost of deploying efficient energy technologies, the development of building energy codes and appliance and equipment standards, the encouragement of voluntary actions to improve energy efficiency, and the continued growth of the broader energy efficiency and energy management industry.[60] The grid is changing with the adoption of new technologies. For example, grid operators are improving system resilience and reliability by installing advanced communications and control technologies as well as automation systems that can detect and react to local changes in usage. On distribution grids, smart meter infrastructure and communication-enabled devices give utilities new abilities to monitor—and potentially lower—electricity usage in real time. These technologies provide operators with access to real-time communications for outages and better tools to prevent outages and manage restoration efforts.

Although most electric service disruptions are caused by transmission and distribution

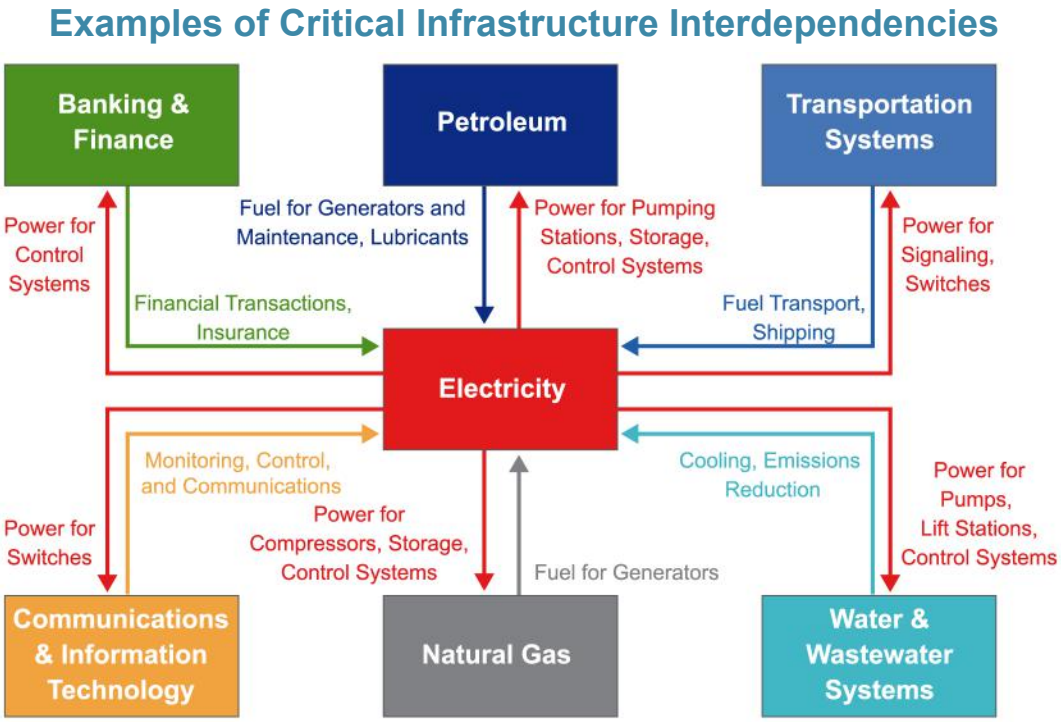


Figure 4.4: The interdependence of critical infrastructure systems increases the importance of electricity resilience, as disruptions to energy services are projected to affect other sectors. Shown above is a representative set of connections, and the complex relationships are analogous to other systems (Ch. 17: Complex Systems). A more complete listing of these linkages can be found at DOE.[2] Source: adapted from DOE 2017.[2]

outages,[1] it is possible for fuel availability to affect electricity generation reliability and resilience. Most generation technologies have experienced fuel deliverability challenges in the past.[31] Coal facilities typically store enough fuel onsite to last for 30 days or more, but extreme cold can lead to frozen fuel stockpiles and disruptions in train deliveries. Natural gas is delivered by pipeline on an as-needed basis. Capacity challenges on existing pipelines, combined with the difficulty in some areas of siting and constructing new natural gas pipelines, along with competing uses for natural gas such as for home heating, have created supply constraints in the past.[31] Renewables supplies are not immune from storage issues, as hydropower is particularly sensitive to water availability and reservoir levels, the magnitude and timing of which will be influenced by a changing climate. Management of the myriad fuel storage challenges and their relation to climate change is a subject that would benefit from improved understanding.

Box 4.2: Changing Dimensions of Energy Security

There is a trend of decreasing net imports (imports minus exports) of petroleum. In 2016, U.S. net imports reached a new low equal to about 25% of U.S. petroleum consumption, down from 60% in 2005.[59,61] This significant decline is the result of several factors, including the exploitation of vast domestic shale oil reserves and, to a lesser extent, reduced demand levels and expanded biofuel production. While this shift has potential national security benefits, there is an accompanying altered geographic distribution of our energy production assets and activities that could result in changes in exposure to the effects of extreme weather and climate change.

Increasing electrification in other sectors—such as telecommunications, transportation (including electric vehicles), banking and finance, healthcare and emergency response, and manufacturing—can exacerbate and compound the impacts of future power outages (Figure 4.4).[2] Like other complex systems (Boxes 4.1 and 4.3) (Ch. 17: Complex Systems), disruptions in other sectors also affect the energy system. For instance, communication architectures, including supervisory control and data acquisition, are often used in power delivery. While increasing automation of these systems on the grid can help mitigate the impact of extreme weather, without appropriate preventive measures, these systems are expected to increase system vulnerabilities to cyberattacks and other systemic risks.[2,31]

Given the interdependencies, resilience actions taken by other sectors to address climate change and extreme weather can have implications for the energy sector. For example, reductions in urban water consumption can result in reductions in electricity use to treat and convey both water and wastewater. California's mandate to reduce urban water consumption to address drought conditions in 2015 resulted in significant reductions in both water use and associated electricity use.[62] Exploring the resilience nexus between sectors can identify the co-benefits of resilience solutions and inform cost-effective resilience strategies.

While the Nation's energy system is changing, it is also aging, with the majority of energy infrastructure dating to the 20th century: 70% of the grid's transmission lines and power transformers are over 25 years old, and the average age of power plants is over 30 years old.[63] The components of the energy system are of widely varying ages and conditions and were not engineered to serve under the extreme weather conditions projected for this century. Aging, leak-prone natural gas distribution pipelines and associated infrastructures prompt safety and environmental concerns.[1]

Without greater attention to aging equipment as well as increasing storm and climate impacts, the U.S. will likely experience longer and more frequent power interruptions.[64]

Key Message 3

Improving Energy System Resilience

Actions are being taken to enhance energy security, reliability, and resilience with respect to the effects of climate change and extreme weather. This progress occurs through improved data collection, modeling, and analysis to support resilience planning; private and public–private partnerships supporting coordinated action; and both development and deployment of new, innovative energy technologies for adapting energy assets to extreme weather hazards. Although barriers exist, opportunities remain to accelerate the pace, scale, and scope of investments in energy systems resilience.

Industry and governments at the local, state, regional, and federal levels are taking actions to improve the resilience of the Nation's energy system and to develop quantitative metrics to assess the economic and energy security benefits associated with these measures. Current efforts include planning and operational measures that seek to anticipate climate impacts and prevent or respond to damages more effectively, as well as hardening measures (including physical barriers, protective casing, or other upgrades) to protect assets from damage, multi-institutional and public–private partnerships for coordinated action, and development and deployment of new technologies to enhance system resilience (Figure 4.5).[3,37,38,39,40,41,42,65]

Energy companies, utilities, and system operators are increasingly employing advanced data, modeling, and analysis to support a range of assessment and planning activities. Accurate load forecasting and generation planning now require considering both extreme weather and climate change. These are also essential considerations for planning and deploying energy infrastructure with a useful service life of decades. Coastal infrastructure plans are beginning to take into account rising sea levels and the associated increased risk of flooding. Resource plans for new thermoelectric power plants and fuel refineries are considering potential changes to fuel and water supplies. For example, the inability of natural gas-fired power plants to store fuel on site is leading energy providers to explore various resilience options, such as co-firing with fuel oil, which can be more readily stored; improving information sharing and coordination between electric generators, gas suppliers, and pipeline operators; and, ensuring the availability of more flexible resources for use to mitigate the uncertainties associated with natural gas fuel risks.[31,66] Advanced tools and techniques are helping planners understand how changes in extreme weather and in the energy system will affect future vulnerabilities and identify the actions necessary to establish a climate-ready energy system.

For the electric grid, improved modeling and analysis of changing generation resources, electricity demand, and usage patterns are helping industry, utilities, and other stakeholders plan for future changes, such as the role of increased storage, demand response, smart grid technologies, energy efficiency, and distributed generation including solar and fuel cells.[67,68] Energy companies, utilities, and system operators are increasingly evaluating long-term capital expansion strategies, their system operations, the resilience of supply chains, and the potential of mutual assistance efforts.[3,29,69]

For example, electricity demand response programs and energy efficiency programs are helping shift or reduce electricity usage during peak periods, improving grid reliability without increasing power generation. A central challenge to such planning is dealing with the broad range of uncertainties inherent to infrastructure investment planning (for example, climate, technology, and load). Advanced tools are being developed that help inform

Energy Sector Resilience Solutions

Flood Protection

- Building/strengthening berms, levees, and floodwalls
- Elevating substations, control rooms, and pump stations
- Expanding wetlands restoration
- Installing flood monitors

Wind Protection

- Inspecting and upgrading poles and structures
- Burying power lines underground
- Improving vegetation management efforts

Drought Protection

- Adopting water efficient thermoelectric cooling
- Utilizing non-freshwater sources
- Expanding low water-use generation

Modernization

- Deploying sensors and control technology
- Installing asset databases/tools, including supervisory control and data acquisition (SCADA) system redundancies
- Deploying energy storage and microgrid infrastructure (distributed energy resources, demand response programs, islanding capabilities)

Advanced Planning and Preparedness

- Conducting extreme weather risk assessment planning, preparedness, and training
- Participating in mutual assistance groups and public–private partnerships
- Purchasing or leasing mobile transformers and substations
- Utilizing geographic information systems (GIS) analysis to help identify vulnerabilities and plan for new builds and relocations

Storm-Specific Readiness

- Coordinating priority restoration and waivers
- Securing emergency fuel contracts
- Improving communication during outages to assist customers

Figure 4.5: Solutions are being deployed in the energy sector to enhance resilience to extreme weather and climate impacts across a spectrum of energy generation technologies, infrastructure, and fuel types. The figure illustrates resilience investment opportunities addressing specific extreme weather threats, as well as broader resilience actions that include grid modernization and advanced planning and preparedness. Photo credits (from top): Todd Plain, U.S. Army Corps of Engineers; Program Executive Office, Assembled Chemical Weapons Alternative; Lance Cheung, USDA; Idaho National Laboratory (CC BY 2.0); Darin Leach, USDA; Master Sgt. Roy Santana, U.S. Air Force.

investment decisions that balance costs as well as risk exposure[70,71,72] in an uncertain future.

Box 4.3: Rebuilding and Enhancing Energy System Resilience: Lessons Learned

While Superstorm Sandy and Hurricanes Harvey, Irma, and Maria caused significant damages to energy infrastructure, these storms also provided an opportunity to rebuild in ways that will enhance resilience to such storms in the future. For example, Superstorm Sandy caused 8.7 million customers to lose power, and utility companies in New York and New Jersey invested billions of dollars in upgrades to protect assets from projected extreme weather and climate change, including installing submersible equipment and floodwalls, elevating equipment, redesigning underground electrical networks, and installing smart switches to isolate and clear trouble on lines.[3,50] These actions have prevented outages to hundreds of thousands of customers and have reduced recovery times.[50] Emerging networks of expert practitioners (such as the National Adaptation Forum), foundation-supported initiatives focusing on cities, and regional events targeting counties and multi-jurisdictional audiences are also providing new forums for information sharing across impacted communities on best practices and low-cost interventions to enhance resilience.

Private and public–private partnerships are increasingly being used to share lessons learned and to coordinate action. Municipal, state, and tribal communities (Ch. 15: Tribes, KM 1) are working together to address climate change related risks,[3,73] as in the case of the Rockefeller Foundation's 100 Resilient Cities and C40 Cities partnerships, which are empowering communities to collaborate, share knowledge, and drive meaningful, measurable, and sustainable action on resilience.[74,75] By way of the U.S. Department of Energy's (DOE) Partnership for Energy Sector Climate Resilience, a number of utilities from across the country are collaborating with the DOE to develop resilience planning guidance, conduct climate change vulnerability assessments, and develop and implement cost-effective resilience solutions.[76] Additionally, the Administration established the Build America Investment Initiative as an interagency effort led by the Departments of Treasury and Transportation to promote increased investment in U.S. infrastructure, particularly through public–private partnerships.

Hardening measures protect energy systems from extreme weather hazards. Measures being adopted include, but are not limited to, adding natural or physical barriers to elevate, encapsulate, waterproof, or protect equipment vulnerable to flooding; reinforcing assets vulnerable to wind damage; adding or improving cooling or ventilation equipment to improve system performance during drought or extreme heat conditions; adding redundancy to increase a system's resilience to disruptions; and deploying distributed generation equipment (such as solar, fuel cells, or small combined-heat-and-power generators), energy storage, and microgrids with islanding capabilities (the ability to isolate a local, self-sufficient power grid during outages) to protect critical services from widespread outages while promoting improved energy efficiency and associated appliance standards. While hardening assets in place may be effective, in other situations, relocating assets may be more cost effective in the longer term.

One key category of hardening measures is addressing the vulnerability of the Nation's energy systems in water-constrained areas (Ch. 3: Water, KM 1). Technologies and practices are available to help address these vulnerabilities (Ch. 17: Complex Systems, KM 3) to thermoelectric power plants, including alternative cooling systems that reduce water withdrawals; nontraditional water sources, including brackish or municipal wastewater;

and power generation technologies that greatly reduce freshwater use, such as wind, photovoltaic solar, and natural gas combined-cycle technologies.[77,78,79,80,81] Technology is also enabling the growing use of produced water (water produced as a byproduct with oil and gas extraction) and brackish groundwater for water-intensive oil and gas drilling techniques.[82] However, expanding the use of non-freshwater sources puts a greater demand on the energy sector to provide the power to capture, treat, and deliver these water supplies.[83,84] Research on innovative future biofuels that are adapted to local climates can also reduce the water needs of biofuels and the possible impacts of a changing climate on the suitability of land for biofuels production.

The current pace, scale, and scope of efforts to improve energy system resilience are likely to be insufficient to fully meet the challenges presented by a changing climate and energy sector, as several key barriers exist. Among these impediments is a lack of reliable projections of climate change at a local level and the associated risks to energy assets, as well as a lack of a national, regional, or local cost-effective risk reduction strategy. This includes a consideration of where adaptation measures are pursued, thereby addressing the uncertainty concerning their effectiveness and the need for additional resilience investments. Addressing these obstacles would benefit from improved awareness of energy asset vulnerability and performance, cost-effective resilience-enhancing energy technologies and operations plans, standardized methodologies and metrics for assessing the benefits of resilience measures, and expanded public–private partnerships to address vulnerabilities collaboratively.[1,2,3,45] Ensuring that poor and marginalized populations, who often face a higher risk from climate change and energy system vulnerabilities, are part of the planning process can help lead to effective resilience actions and provide ancillary co-benefits to society. Energy infrastructure is long-lived and, as a result, today's decisions about how to locate, expand, and modify the Nation's energy system will influence system reliability, resilience, and economic security for decades.[1,2] In addition, without substantial and sustained mitigation efforts to reduce global greenhouse gas emissions, the need for adaptation and resilience investments to address the impacts of climate change on the energy sector is expected to increase if the most severe consequences are to be avoided in the long term.

Acknowledgments

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Opening Image Credit

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Traceable Accounts

Process Description

We sought an author team that could bring diverse experience, expertise, and perspectives to the chapter. Some members have participated in past assessment processes. The team's diversity adequately represents the spectrum of current and projected impacts on the various components that compose the Nation's complex energy system and its critical role to national security, economic well-being, and quality of life. The author team has demonstrated experience in the following areas:

- characterizing climate risks to the energy sector—as well as mitigation and resilience opportunities—at national, regional, and state levels;
- developing climate science tools and information for characterizing energy sector risks;
- supporting local, state, and federal stakeholders with integrating climate change issues into long-range planning;
- analyzing technological, economic, and business factors relevant to risk mitigation and resilience; and
- analyzing energy system sensitivities to drivers such as policy, markets, and physical changes.

In order to develop Key Messages, the author team characterized current trends and projections based on wide-ranging input from federal, state, local, and tribal governments; the private sector, including investor-owned, state, municipal, and cooperative power companies; and state-of-the-art models developed by researchers in consultation with industry and stakeholders. Authors identified recent changes in the energy system (that is, a growing connectivity and electricity dependence that are pervasive throughout society) and focused on how these transitions could affect climate impacts, including whether the changes were likely to exacerbate or reduce vulnerabilities. Using updated assessments of climate forecasts, projections, and predictions, the team identified key vulnerabilities that require near-term attention and highlighted the actions being taken to enhance energy security, reliability, and resilience.

Key Message 1

Nationwide Impacts on Energy

The Nation's energy system is already affected by extreme weather events, and due to climate change, it is projected to be increasingly threatened by more frequent and longer-lasting power outages affecting critical energy infrastructure and creating fuel availability and demand imbalances (*high confidence*). The reliability, security, and resilience of the energy system underpin virtually every sector of the U.S. economy (*high confidence*). Cascading impacts on other critical sectors could affect economic and national security (*high confidence*).

Description of evidence

The energy system's vulnerability to climate change impacts is evidenced through two sources: 1) the historical experience of damage and disruption to energy assets and systems, using data and case studies from events such as Superstorm Sandy and Hurricanes Harvey, Irma, and Maria, as well as the 2011–2016 California drought, and 2) a growing base of scientific literature assessing and projecting the past and future role of climate change in driving damage and disruption to the energy sector. Federal government and international scientific efforts have documented the scope and scale of a changing climate's effects on the U.S. energy system—factors that will need to be considered in long-term planning, design, engineering, operations, and maintenance of energy assets and supply chains if current standards of reliability are to be maintained or improved.[1,2,3,15,23,29,85,86]

This Key Message claims that damage and/or disruption to energy systems is more likely in the future. This claim is based on the following specific climate change projections and their expected impacts on energy systems:

- higher maximum air temperatures during heat waves and associated impacts on energy generation, delivery, and load (*very likely*, *very high confidence*)[3,53]
- higher average air temperatures and associated increases in energy demand for cooling (*very likely*, *very high confidence*)[11,12,13,14,15,16,17,18,19,53]
- higher surface water temperatures and associated impacts on thermoelectric power generation (*very likely*, *very high confidence*)[3,87]
- shifts in streamflow timing in snow-dominated watersheds to earlier in the year[8] and associated impacts on hydropower generation (*very likely*, *very high confidence*)[86,88]
- increased frequency and intensity of drought (*very likely*, *high confidence*)[54] and associated impacts on biofuels production[3]
- more frequent, intense, and longer-duration drought, particularly in snow-dominated watersheds in the western United States,[54] and associated threat to hydropower production, oil and gas extraction and refining, and thermoelectric cooling[3,21,22,24,88]
- increased wind intensity from Atlantic and eastern Pacific hurricanes (*medium confidence*)[55] and associated impacts on coastal energy infrastructure[3]
- increased rain intensity for hurricanes (*high confidence*) and increased frequency and intensity of heavy precipitation events (*high confidence*), including West Coast atmospheric river events (*medium confidence*),[89] and associated impacts on energy infrastructure[3]
- increased relative sea level rise (*very high confidence*)[47] and associated risk of enhanced flooding of coastal infrastructure as well as inland energy infrastructure along rivers[3]
- increased frequency and intensity of heavy precipitation (*very likely*)[89] and associated impacts to inland flooding of energy assets[3,15]

- increased frequency of occurrence of conditions that support the formation of convective storms (thunderstorms, tornadoes, and high winds)[55] and associated damage to electricity transmission and distribution lines (*low confidence*)[1,3]

The effects of extreme weather on energy system infrastructure have been well documented by researchers and synthesized into several assessment reports produced by federal agencies.[2,3,15,23] The link between extreme weather and power outages is strongest: extreme weather is the leading cause of power outages in the United States.[2] Increased wind speeds and precipitation have been correlated with increased outage duration, and wind speeds have also been correlated with outage frequency.[90] Claims regarding fuel shortages are also based on historical experience; Superstorm Sandy led to local fuel distribution shortages, while Hurricane Katrina led to fuel production and refining shortages with national impacts.[3] The claim that energy system outages can increase energy prices, negatively affect economic growth, and disrupt critical services essential for health and safety is likewise substantiated by the historical experience of severe storms, flooding, and widespread power outages.[23]

Major uncertainties

The inability to predict future climate parameters with complete accuracy is one primary uncertainty that hinders energy asset owners, operators, and planners from anticipating, planning for, and acting on vulnerabilities to climate change and extreme weather. All climate change projections include a degree of uncertainty, owing to a variety of factors, including incomplete historical data, constraints on modeling methodologies, and uncertainty about future emissions. For some climate parameters, confidence in both the direction and magnitude of projected change is high, so expected impacts to the energy sector are well understood. For example, projected temperature changes across the United States uniformly indicate that the demand for cooling energy is projected to increase and the demand for heating energy is projected to decrease.[8,15]

However, confidence is generally lower for other climate parameters projections, making it difficult to understand and prioritize the risks associated with climate hazards and lowering confidence levels in related energy sector impacts. There is uncertainty in projections regarding changes in the frequency and intensity of hurricanes and convective storms, the magnitude and timing of sea level rise, the connection between projected changes in precipitation and the likelihood of droughts and flooding, and the potential increased seasonal variability in wind and solar resources. Hurricanes and convective storms represent major threats to energy infrastructure in general and to electricity transmission and distribution grids in particular.[1,3] However, historical data for hurricanes and convective storms (including tornadoes, hail, and thunderstorms) are lacking and inconsistent over different time periods and regions, and they can be biased based on population density and shifting populations.[55] Furthermore, for convective storms, most global climate models are not capable of modeling the atmosphere at a small enough scale to directly simulate storm formation.[8] Projections of changes in sea level rise and impacts on coastal energy infrastructure are improving, but significant uncertainty regarding the magnitude of long-term sea level rise impedes energy system planners' ability to make decisions about infrastructure with useful lifetimes of 50 years or more.[47] Global climate models are also insufficient to project future hydrological changes, as these projections lack sufficient spatial and temporal resolution and lack detail about other factors important to local hydrology, including changes to soil, groundwater, and water withdrawal and consumption. A lack of hydrological projections increases uncertainty

about water availability consequences for hydropower and thermoelectric power plants and oil and gas extraction.

Description of confidence and likelihood

Climate change is projected to affect the energy sector in many ways, but the overall effect of rising temperatures, changing precipitation patterns, and increases in the frequency and/or severity of extreme weather is to increase the risk of damage or disruption to energy sector assets and energy systems. The combined projection of increasing risk of damage or disruption is *very likely*, with *high confidence*.

Key Message 2

Changes in Energy System Affect Vulnerabilities

Changes in energy technologies, markets, and policies are affecting the energy system's vulnerabilities to climate change and extreme weather. Some of these changes increase reliability and resilience, while others create additional vulnerabilities (*very likely, very high confidence*). Changes include the following: natural gas is increasingly used as fuel for power plants; renewable resources are becoming increasingly cost competitive with an expanding market share; and a resilient energy supply is increasingly important as telecommunications, transportation, and other critical systems are more interconnected than ever.

Description of evidence

Large-scale changes in the energy sector are primarily evidenced through the U.S. Energy Information Administration's (EIA) data collection and analysis. EIA collects monthly and annual surveys from every U.S. power plant; findings include the types of fuel each plant uses.[22] Several sources support claims that renewable technology deployment is growing while costs are falling: EIA data,[22,25] National Renewable Energy Laboratory research,[26] and multiple studies.[27,28,30,32,33] The U.S. Department of Energy's *Quadrennial Energy Review*[1,2] and other reviews[31] provide analysis that supports the growing integration of energy systems into other sectors of the economy.

Major uncertainties

Future changes in the energy system, and the effect on energy system vulnerabilities to extreme weather and climate change, are uncertain and will depend on numerous factors that are difficult to predict, including macroeconomic and population growth; financial, economic, policy, and regulatory changes; and technological progress. Each of these factors can affect the cost of technologies, the growth in energy demand, the rate of deployment of new technologies, and the selection of sites for deployment.

Description of confidence and likelihood

The reliable production and delivery of power enables modern electricity-dependent critical infrastructures to support American livelihoods and the national economy. There is *very high confidence* that a deepening dependence on electric power and increasing interdependencies within the energy system can increase the vulnerabilities and risks associated with extreme weather and climate hazards in some situations (*very likely, very high confidence*).

There is *very high confidence* that many trends in the changing energy system are *very likely* to continue and that changes will have potential effects on reliability and resilience. A primary factor affecting the increased use of natural gas and the deployment of renewable resources is the relative price of these generation sources. Existing proven resources of natural gas are sufficient to supply current demand for several decades.[91] Renewable technologies are *very likely* to continue falling in price, as manufacturers continue to improve their processes and take advantage of economies of scale.[92] The degree of interconnection of critical systems is also *very likely* to increase. The continued deployment of smart grid devices, microgrids, and energy storage will *likely* provide multiple reliability and resilience benefits.[2]

Key Message 3

Improving Energy System Resilience

Actions are being taken to enhance energy security, reliability, and resilience with respect to the effects of climate change and extreme weather *(very high confidence)*. This progress occurs through improved data collection, modeling, and analysis to support resilience planning; private and public–private partnerships supporting coordinated action; and both development and deployment of new, innovative energy technologies for adapting energy assets to extreme weather hazards. Although barriers exist, opportunities remain to accelerate the pace, scale, and scope of investments in energy systems resilience *(very high confidence)*.

Description of evidence

Several entities have identified evidence for the planning and deployment of resilience solutions in the energy sector. Support comes from both industry and federal agencies, including the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), and the Department of Homeland Security (DHS).[3,37,38,39,40,41,42] For example, the DOE's recent efforts, reflected in the *Quadrennial Energy Review*[1,2] and the *Quadrennial Technology Review*,[45] examine how to modernize our Nation's energy system and technologies to promote economic competitiveness, energy security and reliability, and environmental responsibility. Through the Partnership for Energy Sector Climate Resilience, the DOE and partner utilities provide examples of plans and implementation of resilience solutions, as well as barriers to expanded investments in resilience.[3,76] This Key Message gains further support from the EPA's work with industry and local and state governments through its Creating Resilient Water Utilities program,[93] as well as from the collaboration of the DHS with private sector critical infrastructure owners and operators through its National Infrastructure Protection Plan Security and Resilience Challenge.[94] In addition, a growing constituency of cities, municipalities, states, and tribal communities are dedicating resources and personnel toward identifying, quantifying, and responding to climate change related risks to energy system reliability and the social services that depend on those systems.[3,73] For example, the Rockefeller Foundation's 100 Resilient Cities and C40 Cities are both networks of the world's cities committed to addressing resilience. These coalitions, including multiple U.S. cities, support cities in their efforts to collaborate effectively, share knowledge, and drive meaningful, measurable, and sustainable action on resilience.[74,75]

Major uncertainties

The most significant uncertainties affecting future investments in climate resilience are related to evaluating the costs, benefits, and performance of resilience investments—and the costs of inaction. To make informed investments, decision-makers need standardized cost–benefit frameworks and methodologies, as well as reliable, high-resolution (temporal and spatial) climate change projections of critical weather and climate parameters.[1,2,3,76]

The high complexity of the energy system introduces uncertainty in whether particular actions could yield unintended consequences. Using the examples above, energy storage, distributed generation, microgrids, and other technologies and practices can contribute to resilience. However, unless evaluated in a systematic manner, the adoption of technologies and practices will likely lead to unintended consequences, including environmental (such as air quality), economic, and policy impacts.

Significant uncertainty is also found in the future pace of mitigation efforts that will, in turn, influence the need for resilience investments. Some level of climate change will continue, given past and current emissions of heat-trapping greenhouse gases. However, without an effective mitigation strategy, the need for additional adaptation and resilience investments becomes greater. Uncertainty about the rate of stabilizing and reducing greenhouse gas emission levels (mitigation) compounds the challenge of characterizing the magnitude and timing of additional resilience investments.

The pace of development and deployment of resilient cost-effective energy technologies are also uncertain and will likely be critical to implementing resilience strategies at scale. These technologies will likely include improvements in areas such as energy storage, distributed generation, microgrids, and cooling for thermoelectric power plants.[1,2,3,31,76]

Description of confidence and likelihood

There is *very high confidence* that many of the technologies and planning or operational measures necessary to respond to climate change exist and that their implementation is in progress.[29] Although federal, state, local, and tribal governments and the private sector are already responding, there is *very high confidence* that the pace, scale, and scope of combined public and private efforts to improve preparedness and resilience of the energy sector are likely to be insufficient, given the nature of the challenge[1,2,3,29,31] presented by a changing climate and energy sector.

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5 Land Cover and Land-Use Change

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5 Land Cover and Land-Use Change

Agricultural fields near the Ririe Reservoir, Bonneville, Idaho

Key Message 1

Land-Cover Changes Influence Weather and Climate

Changes in land cover continue to impact local- to global-scale weather and climate by altering the flow of energy, water, and greenhouse gases between the land and the atmosphere. Reforestation can foster localized cooling, while in urban areas, continued warming is expected to exacerbate urban heat island effects.

Key Message 2

Climate Impacts on Land and Ecosystems

Climate change affects land use and ecosystems. Climate change is expected to directly and indirectly impact land use and cover by altering disturbance patterns, species distributions, and the suitability of land for specific uses. The composition of the natural and human landscapes, and how society uses the land, affects the ability of the Nation's ecosystems to provide essential goods and services.

Executive Summary

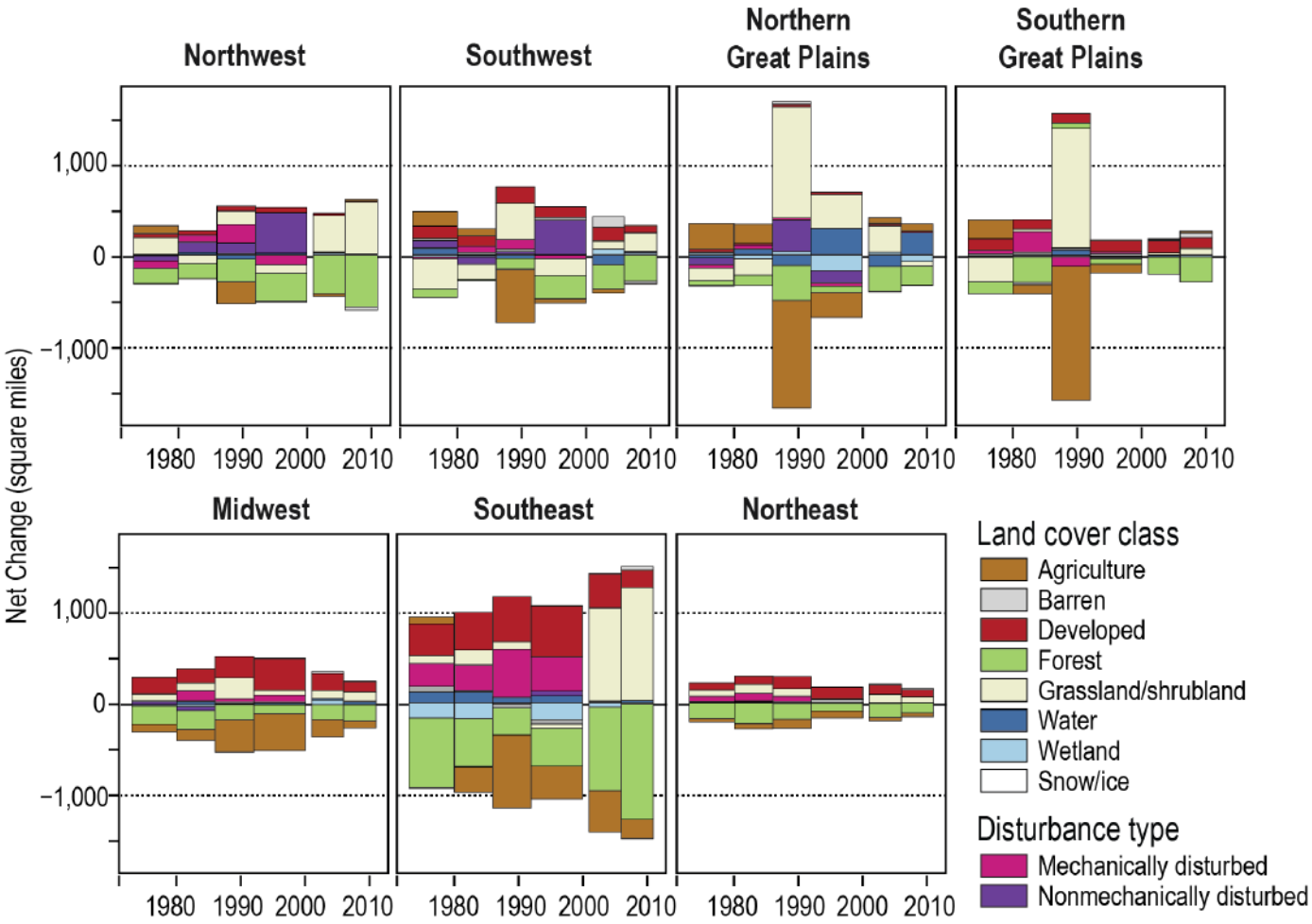
Climate can affect and be affected by changes in land cover (the physical features that cover the land such as trees or pavement) and land use (human management and activities on land, such as mining or recreation). A forest, for instance, would likely include tree cover but could also include areas of recent tree removals currently covered by open grass areas. Land cover and use are inherently coupled: changes in land-use practices can change land cover, and land cover enables specific land uses. Understanding how land cover, use, condition, and management vary in space and time is challenging.

Changes in land cover can occur in response to both human and climate drivers. For example, demand for new settlements often results in the permanent loss of natural and working lands, which can result in localized changes in weather patterns, temperature, and precipitation. Aggregated over large areas, these changes have the potential to influence Earth's climate by altering regional and global circulation patterns, changing the albedo (reflectivity) of Earth's surface, and changing the amount of carbon dioxide (CO_2) in the atmosphere. Conversely, climate change can also influence land cover, resulting in a loss of forest cover from climate-related increases in disturbances, the expansion of woody vegetation into grasslands, and the loss of beaches due to coastal erosion amplified by rises in sea level.

Land use is also changed by both human and climate drivers. Land-use decisions are traditionally based on short-term economic factors. Land-use changes are increasingly being influenced by distant forces due to the globalization of many markets. Land use can also change due to local, state, and national policies, such as programs designed to remove cultivation from highly erodible land to mitigate degradation,[1] legislation to address sea level rise in local comprehensive plans, or policies that reduce the rate of timber harvest on federal lands. Technological innovation has also influenced land-use change, with the expansion of cultivated lands from the development of irrigation technologies and, more recently, decreases in demand for agricultural land due to increases in crop productivity. The recent expansion of oil and gas extraction activities throughout large areas of the United States demonstrates how policy, economics, and technology can collectively influence and change land use and land cover.

Decisions about land use, cover, and management can help determine society's ability to mitigate and adapt to climate change.

Changes in Land Cover by Region



The figure shows the net change in land cover by class in square miles, from 1973 to 2011. Land-cover change has been highly dynamic over space, time, and sector, in response to a range of driving forces. Net change in land cover reveals the trajectory of a class over time. A dramatic example illustrated here is the large decline in agricultural lands in the two Great Plains regions beginning in the mid-1980s, which resulted in large part from the establishment of the Conservation Reserve Program. Over the same period, agriculture also declined in the Southwest region; however, the net decline was largely attributable to prolonged drought conditions, as opposed to changes in federal policy. Data for the period 1973–2000 are from Sleeter et al. (2013)[2] while data from 2001–2011 are from the National Land Cover Database (NLCD).[3] Note: the two disturbance categories used for the 1973–2000 data were not included in the NLCD data for 2001–2011 and largely represent conversions associated with harvest activities (mechanical disturbance) and wildfire (nonmechanical disturbance). Comparable data are unavailable for the U.S. Caribbean, Alaska, and Hawai'i & U.S.-Affiliated Pacific Islands regions, precluding their representation in this figure. *From Figure 5.2 (Source: USGS).*

Introduction

Climate can affect and be affected by changes in land cover (the physical features that cover the land, such as trees or pavement) and land use (human management and activities on land, such as mining or recreation). A forest, for instance, would likely include tree cover but could also include areas of recent tree removals currently covered by open grass areas. Land cover and use are inherently coupled: changes in land-use practices can change land cover, and land cover enables specific land uses. Understanding how land cover, use, condition, and management vary in space and time is challenging, because while land cover and condition can be estimated using remote sensing techniques, land use and management typically require more local information, such as field inventories. Identifying, quantifying, and comparing estimates of land use and land cover are further complicated by factors such as consistency and the correct application of terminology and definitions, time, scale, data sources, and methods. While each approach may produce land-use or land-cover classifications, each method may provide different types of information at various scales, so choosing appropriate data sources and clearly defining what is being measured and reported are essential.

Changes in land cover can occur in response to both human and climate drivers. For example, the demand for new settlements often results in the permanent loss of natural and working lands, which can result in localized changes in weather patterns,[4,5] temperature,[6,7] and precipitation.[8] Aggregated over large areas, these changes have the potential to influence Earth's climate by altering regional and global circulation patterns,[9,10,11] changing the albedo (reflectivity) of Earth's surface,[12,13] and changing the amount of carbon dioxide (CO_2) in the atmosphere.[14,15] Conversely, climate change can also influence land cover, resulting in a loss of forest cover from climate-related increases in disturbances,[16,17,18] the expansion of woody vegetation into grasslands,[19] and the loss of coastal wetlands and beaches due to increased inundation and coastal erosion amplified by rises in sea level.[20]

Changes in land use can also occur in response to both human and climate drivers. Land-use decisions are often based on economic factors.[21,22,23] Land-use changes are increasingly being influenced by distant forces due to the globalization of many markets.[21,24,25,26] Land use can also change due to local, state, and national policies, such as programs designed to remove cultivation from highly erodible land to mitigate degradation,[1] legislation to address sea level rise in local comprehensive plans,[27] and policies that reduce the rate of timber harvest on federal lands[28,29] or promote the expansion of cultivated lands for energy production.[30] Technological innovation has also influenced land-use change, with the expansion of cultivated lands from the development of irrigation technologies[31,32] and, more recently, decreases in demand for agricultural land due to increases in crop productivity.[33] The recent expansion of oil and gas extraction activities throughout large areas of the United States demonstrates how policy, economics, and technology can collectively influence and change land use and land cover.[34]

Land use also responds to changes in climate and weather. For example, arable land (land that is suitable for growing crops) may be fallowed (left uncultivated) or abandoned completely during periods of episodic drought[35,36] or converted to open water during periods of above-normal precipitation.[37] Increased temperatures have also been shown to have a negative effect on agricultural yields (Ch. 10: Ag & Rural, KM 1).[38] Climate change can also have positive impacts on land use, such as increases

in the length of growing seasons, particularly in northern latitudes.[39,40,41] Forest land use is also susceptible to changes in weather and climate (Ch. 6: Forests). For example, the recent historical drought in California has resulted in a significant forest die-off event,[42,43] which has implications for commercial timber production. Similarly, insect outbreaks across large expanses of western North American forests have been linked to changes in weather and climate,[17] which in turn may result in important feedbacks on the climate system.[44] Sea level rise associated with climate change will likely require changes in coastal land use, as development and infrastructure are increasingly impacted by coastal flooding.[27,45,46,47] As sea levels rise, many coastal areas will likely experience increased frequency and duration of flooding events, and impacts may be felt in areas that have not experienced coastal flooding in the past (Ch. 8: Coastal, KM 1).

Decisions about land use, cover, and management can help determine society's ability to mitigate and adapt to climate change. Reducing atmospheric greenhouse gas (GHG) concentrations can, in part, be achieved by increasing the land-based carbon storage.[48] Increasing this carbon storage can be achieved by increasing the area of forests, stabilizing or increasing carbon stored in soils[49,50] and forests (Ch. 6: Forests),[51] avoiding the release of stored carbon due to disturbances (such as wildfire) through forest management practices (Ch. 6: Forests, KM 3),[52,53] and increasing the carbon stored in wood products.[54] However, there are large uncertainties about what choices will be made in the future and the net effects of the resulting changes in land use and land cover.[55,56,57]

State of the Sector

Humans have had a far-reaching impact on land cover within the contiguous United States. Of the approximately 3.1 million square miles of land area, approximately 28% has been significantly altered by humans for use as cultivated cropland and pastures (22%) or settlements (6%; Figure 5.1a).[3] Land uses associated with resource production (such as grazing, cropland, timber production, and mining) account for more than half of the land area of the contiguous United States,[58] followed by land that is conserved (16%), built-up areas (13%), and recreational land (10%; Figure 5.1b). Between 2001 and 2011, developed land cover increased by 5% and agriculture declined by 1%. Urbanization was greater between 2001 and 2006 than between 2006 and 2011, which may be attributable to the 2007–2009 economic recession.[59,60] The relative stability in agricultural land use between 2001 and 2011 masks widespread fluctuations brought about by the abandonment and expansion of agricultural lands (see Figure 5.2 for more detail).

Vegetated land cover, including grasslands, shrublands, forests, and wetlands, accounted for approximately two-thirds of the contiguous U.S. land area and experienced a net decline of approximately 5,150 square miles between 2001 and 2011. However, many of these areas are also used for the production of ecosystem goods and services, such as timber and grazing, which lead to changes in land cover but may not necessarily result in a land-use change. Between 2001 and 2011, forest land cover had the largest net decline of any class (25,730 square miles)[3] but forest land use increased by an estimated 3,200 square miles over a similar period (Ch. 6: Forests).[61] The increase in forest land use is due, in large part, to the conversion

Land-Use and Land-Cover Composition

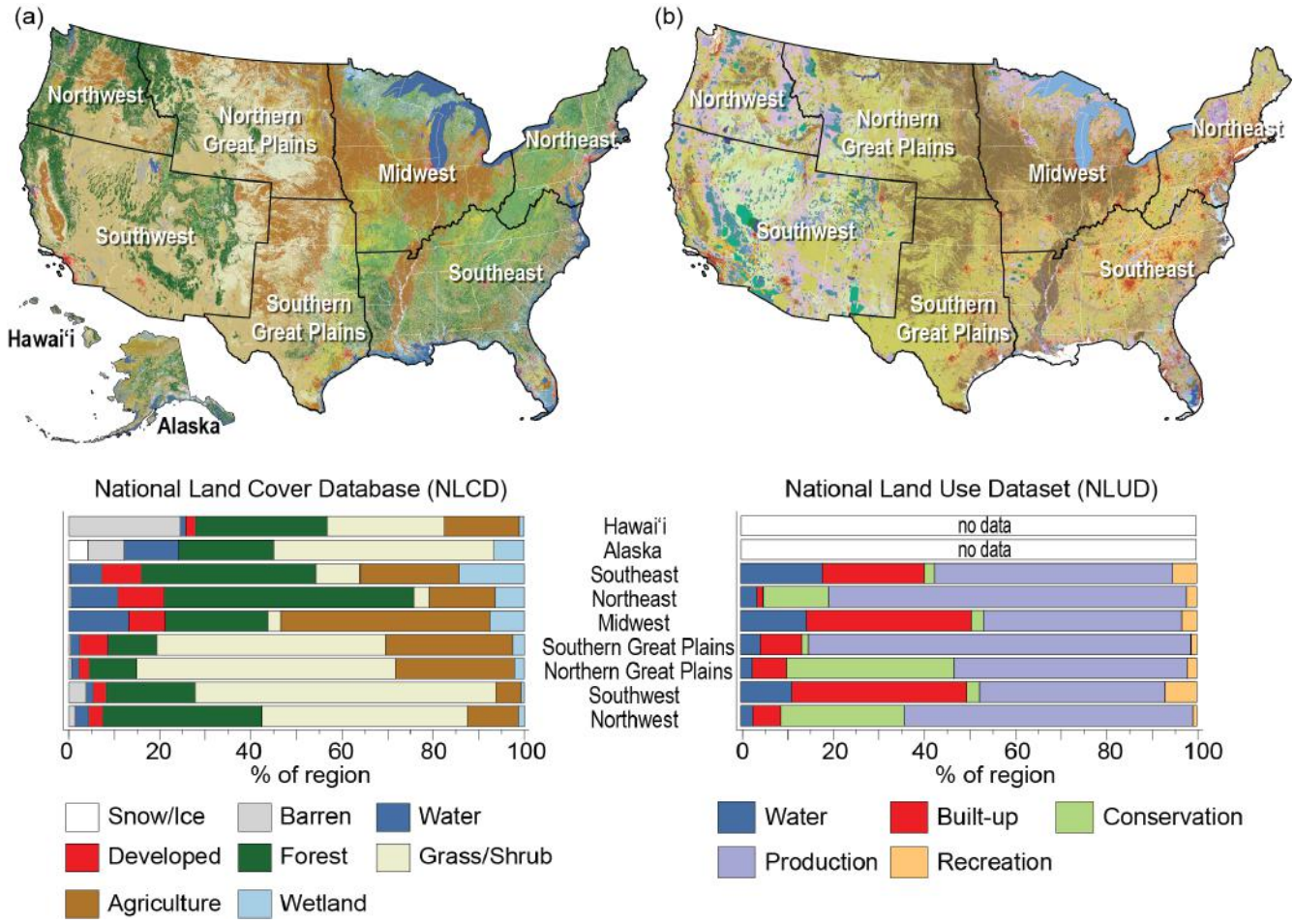


Figure 5.1: The composition of land use and land cover (LULC) is highly variable across the United States, owing in part to the natural environmental settings of each region. Forests dominate much of the vegetated areas of the eastern United States, while much of the Great Plains and Southwest are dominated by grasses and shrubs. Characterizing the composition of LULC also depends on the type of classification system used. This figure shows two different classification systems used to represent different components of land use and land cover: (a) the National Land Cover Database (NLCD),[3] which is derived from the classification of satellite images and represents the physical features on the ground, such as land that is covered by trees (forest cover) or impervious surfaces (developed cover); and (b) the National Land Use Dataset (NLUD),[58] which divides the land into 79 land-use categories that can be aggregated into five major use categories, including lands used for conservation, production of goods and services, and recreation. Data are unavailable for both the U.S. Caribbean region and the U.S.-Affiliated Pacific Islands in the NLCD and the NLUD. Source: USGS.

Estimates of Land-Use Area (Square Miles) by NCA Region

NCA Region	Croplands	Forestlands	Grasslands	Other Lands	Settlements	Wetlands
Alaska	111	133,438	305,659	76,388	558	64,336
Hawai'i	173	2,501	1,997	1,283	438	51
Midwest	212,994	142,314	43,753	4,140	36,638	18,867
Northern Great Plains	136,089	62,829	248,678	4,473	8,216	9,765
Northeast	24,490	131,383	11,649	2,929	24,856	12,521
Northwest	28,076	114,263	89,963	3,853	7,784	5,573
Southern Great Plains	103,698	103,325	182,216	2,547	19,878	7,790
Southeast	84,137	301,616	58,442	3,610	45,799	34,852
Southwest	39,782	174,669	416,464	30,324	22,311	10,237
Total	**629,550**	**1,166,338**	**1,358,821**	**129,547**	**166,478**	**163,992**

Table 5.1: Definitions of land use and land cover vary among agencies and entities collecting those data. This may lead to fundamental differences in these estimates that must be considered when comparing estimates of cover and use. For the purposes of this report, land cover is defined as the physical characteristics of land, such as trees or pavement, and land use is characterized by human management and activities on land, such as mining or recreation. The land-use area estimates in this table and throughout this chapter were obtained from the U.S. Forest Service's Forest Inventory and Analysis (FIA) Program and the National Resources Conservation Service's (NRCS) Natural Resources Inventory (NRI) data, when available for an area, because the surveys contain additional information on management, site conditions, crop types, biometric measurements, and other data that are needed to estimate carbon stock changes and nitrous oxide and methane emissions on those lands. If NRI and FIA data are not available for an area, however, then the NLCD product is used to represent the land use. Since all three data sources were used in the land representation analysis within the National Inventory Report, we used land-use estimates from the U.S. Environmental Protection Agency's annual greenhouse gas inventory report.[61] Data are unavailable for both the U.S. Caribbean region and the U.S.-Affiliated Pacific Islands in the NRI and FIA datasets.

of abandoned croplands to forestland[62] and the reversion to and expansion of trees in grassland ecosystems in the Great Plains and western United States.[61] There have also been losses in forest land use over the past 25 years, predominantly to grasslands and settlements, with grasslands and shrublands increasing in area by nearly 20,460 square miles. Collectively, non-vegetated areas, including water, barren areas, and snow and ice, account for approximately 6% of the total land area.

Coastal regions, as mapped within the National Oceanic and Atmospheric Administration's (NOAA) Coastal Change Analysis Program (C-CAP), account for 23% of the contiguous U.S. land area and have been particularly dynamic in terms of change, accounting for approximately 50% of all land-cover change and 43% of all urbanization in the contiguous United States. Approximately 8% of the coastal region changed between 1996 and 2010, which included about 16,500 square miles of forest loss and about 5,700 square miles of gain in urban land, a rate three times higher than that of the interior of the United States. Additionally, nearly 1,550 square miles of wetlands were lost in coastal regions, a trend counter to that of the Nation as a whole. A majority of this wetland loss has occurred in the northern Gulf of Mexico (Ch. 8: Coastal; Ch. 19: Southeast).[63] Coastal shoreline counties comprise approximately 10% of the United States in terms of land cover (excluding Alaska and the U.S. Caribbean) yet represent 39% of the U.S. population (2010 estimates), with population densities six times higher than in non-coastal areas.[64] Between 1970 and 2010, the population in coastal areas increased by nearly 40% and is projected to increase by an additional 10 million people over 2010–2020 (Figure 5.3).[64] Increases in the frequency of high tide

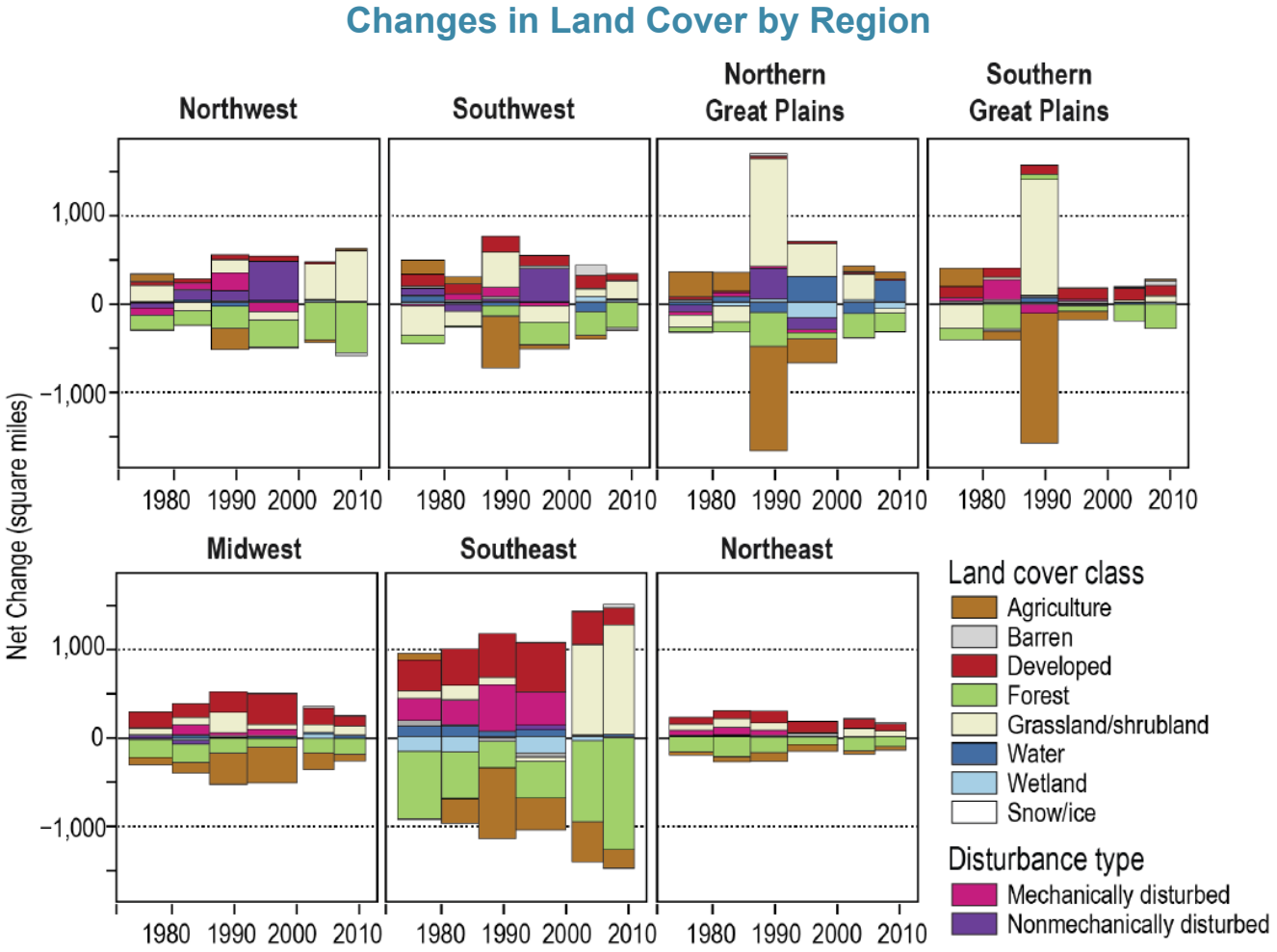


Figure 5.2: The figure shows the net change in land cover by class in square miles, from 1973 to 2011. Land-cover change has been highly dynamic over space, time, and sector, in response to a range of driving forces. Net change in land cover reveals the trajectory of a class over time. A dramatic example illustrated here is the large decline in agricultural lands in the two Great Plains regions beginning in the mid-1980s, which resulted in large part from the establishment of the Conservation Reserve Program. Over the same period, agriculture also declined in the Southwest region; however, the net decline was largely attributable to prolonged drought conditions, as opposed to changes in federal policy. Data for the period 1973–2000 are from Sleeter et al. (2013),[2] while data from 2001–2011 are from the National Land Cover Database (NLCD).[3] Note: the two disturbance categories used for the 1973–2000 data were not included in the NLCD data for 2001–2011 and largely represent conversions associated with harvest activities (mechanical disturbance) and wildfire (nonmechanical disturbance). Comparable data are unavailable for the U.S. Caribbean, Alaska, and Hawai'i & U.S.-Affiliated Pacific Islands regions, precluding their representation in this figure. Source: USGS.

flooding and extreme weather events (such as hurricanes and nor'easters), wetland loss, and beach loss from sea level rise present potential threats to people and property in the coastal zone (Ch. 8: Coastal, KM 1; Ch. 18: Northeast; Ch. 19: Southeast, KM 2).

Disturbance events (such as wildfire and timber harvest) are important factors that influence land cover. For example, forest disturbances can initiate a succession from forest to herbaceous grasslands to shrublands before forest reestablishment, with each successional stage having a different set of feedbacks with the climate. The length of an entire successional stage varies based on local environmental characteristics.[65] Permanent transitions to new cover types after a disturbance are also possible for many reasons, including the establishment of invasive or introduced species that are able to quickly establish and outcompete native vegetation.[66,67] Data from the North American Forest Dynamics dataset indicate that forest disturbances affected an

Development in the Houston Area

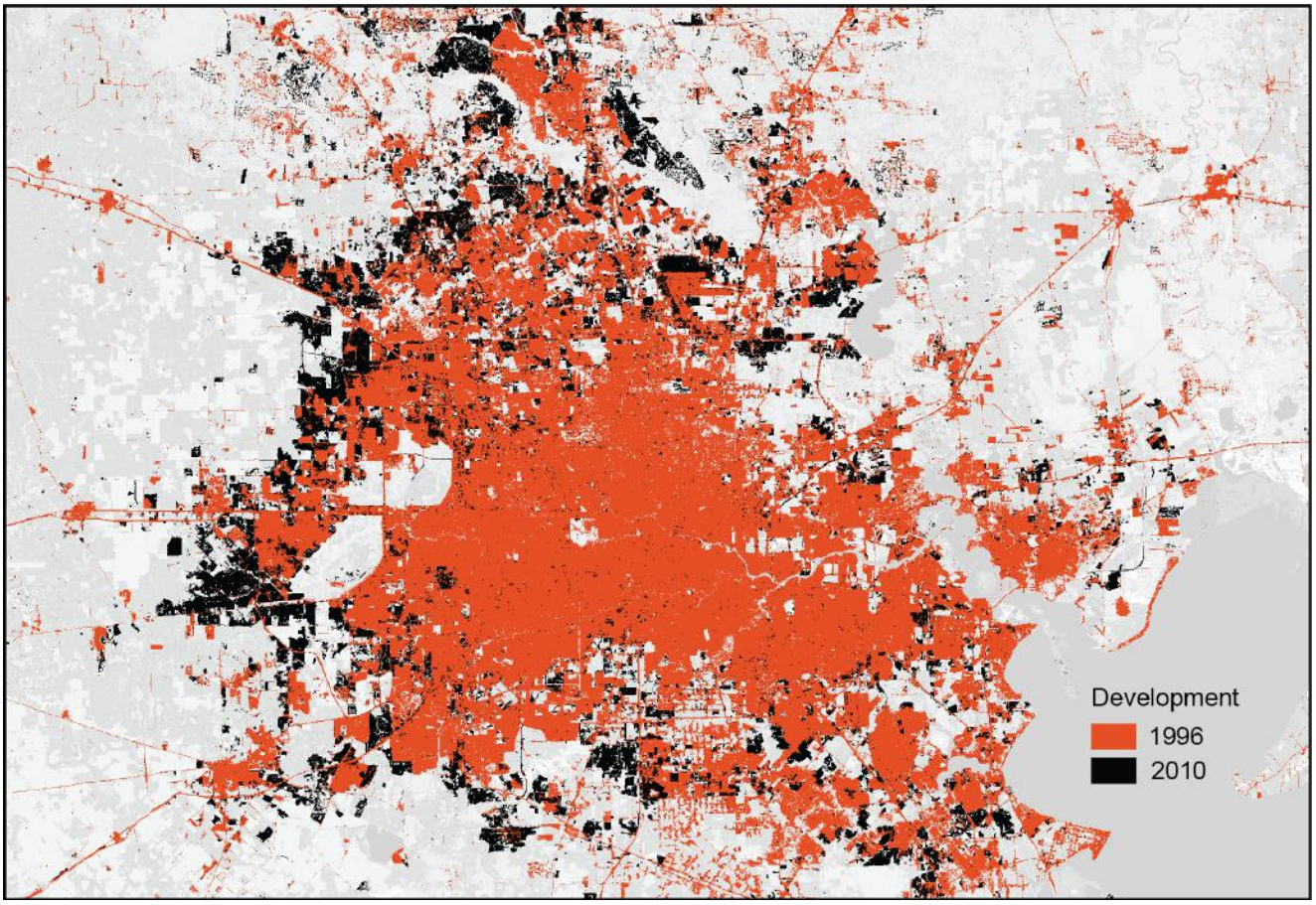


Figure 5.3: The figure shows the development-related changes surrounding Houston, Texas, from 1996 to 2010, as mapped by NOAA's Coastal Change and Analysis Program (C-CAP). Areas of change between 1996 and 2010 are shown in black.[63] These changes can have numerous impacts on the environment and populations, ranging from increased urban heat island effects and storm water runoff (the latter of which can increase flooding and produce water quality impacts), to decreases in natural cover. Source: USGS.

average of approximately 11,200 square miles per year in the contiguous United States from 1985 to 2010 (an area greater than the entire state of Massachusetts). Between 2006 and 2010, the rate of forest disturbance declined by about one-third.[68] Although these data include a wide range of disturbance agents, including fire, insects, storms, and harvest, the sharp decline likely corresponds to a reduction in timber harvest activities resulting from a drop in demand for construction materials following the 2007–2009 economic recession.

Wildland fires provide a good example of how ecosystem disturbance, climate change, and land management can interact. Between 1979 and 2013, the number of days with weather conditions conducive to fire has increased globally, including in the United States.[69] At the same time, human activities have expanded into areas of uninhabited forests, shrublands, and grasslands,[70] exposing these human activities to greater risk of property and life loss at this wildland–urban interface.[71,72] Over the last two decades, the amount of forest area burned and the expansion of human activity into forests and other wildland areas have increased.[73] These changes in climate and patterns of human activity have led in part to the development of a national strategy for wildland fire management for the United States. The strategy, published in 2014, was one outcome of the Federal Land Assistance, Management, and Enhancement (FLAME) Act of

2009. An important component of the national strategy[74] is a classification of U.S. counties based on their geographic context; fire history; amount of urban, forest, and range land; and other factors. The land-use, land-cover, and other components of the classification model are used to guide management actions.

Future Changes

Representative Concentration Pathways (RCPs) were developed to improve society's understanding of plausible climate and socioeconomic futures.[75] U.S. projections of land-use and land-cover change (LULCC) developed for the RCPs span a wide range of future climate conditions, including a higher scenario (RCP8.5)[76] and three mitigation scenarios (RCP2.6, RCP4.5, and RCP6.0) (for more on RCPs, see Front Matter and the Scenario Products section in App. 3).[77,78,79] Projected changes in land use within each scenario were harmonized with historical data[80] and include a broad range of assumptions, from aggressive afforestation (the establishment of a forest where there was no previous tree cover) in the Midwest and Southeast (RCP4.5) to large-scale expansion of agricultural lands to meet biofuel production levels (RCP2.6; see Hibbard et al. 2017 [81]).

The Shared Socioeconomic Pathways (SSPs) have been developed to explore how future scenarios of climate change interact with alternative scenarios of socioeconomic development (in terms of population, economic growth, and education) to understand climate change impacts, adaptation and mitigation, and vulnerability.[82,83] In a scenario with medium barriers to climate mitigation and adaptation (SSP2) and a scenario with high barriers to climate mitigation (SSP5), the amount of land devoted to developed use (for example, urban and suburban areas) is projected to increase by 50% and 80%, respectively, from 2010 levels by the year 2100. These changes represent a potential loss of between 500,000 and 620,000 square miles of agricultural or other vegetated lands (for more on SSPs, see the Scenario Products section of App. 3).[84]

Future changes in land use are likely to have far-reaching impacts on other sectors. For example, by mid-century, water use in California is projected to increase by 1.5 million acre-feet, driven almost entirely by a near 60% increase in developed water-use demand.[85] Research in Hawai'i projects a steady reduction in the strength of the state's annual ecosystem carbon sink, resulting primarily from a combination of urbanization and a shift toward drier, less productive ecosystems by mid-century.[86]

Key Message 1

Land-Cover Changes Influence Weather and Climate

Changes in land cover continue to impact local- to global-scale weather and climate by altering the flow of energy, water, and greenhouse gases between the land and the atmosphere. Reforestation can foster localized cooling, while in urban areas, continued warming is expected to exacerbate urban heat island effects.

The influence of land-use and land-cover change (LULCC) on climate and weather is complex, and specific effects depend on the type of change, the scale of the assessment (local, regional, or global), the size of the area under consideration, the aspect of climate and weather being evaluated (such as temperature, precipitation, or seasonal trends), and the region where the change occurs.[87,88]

Recent studies suggest that forests tend to be cooler than herbaceous croplands throughout much of the temperate region.[89,90,91,92,93,94,95,96]

These studies suggest that reforestation in the temperate forest region would promote cooling, with the magnitude of cooling decreasing with increasing latitude.[90,94,95,96,97] The scale of the cooling from reforestation would depend on its extent and location. Biogeophysical (albedo, surface roughness, and transpiration) changes arising from land-cover change tend to result in more localized changes, whereas biogeochemical changes (such as carbon sequestration) tend to have a more global reach. Reforestation in the temperate forest region is an effective climate mitigation and adaptation strategy.[90,94]

Fires in forests, grasslands, shrublands, and agricultural lands affect climate in two ways: 1) transporting carbon from the land to the atmosphere in the form of carbon dioxide and other greenhouse gases, and 2) increasing the concentration of small particles (aerosols) in the atmosphere that tend to reduce the amount of solar energy reaching the surface of Earth by increasing (although often temporarily) the reflectivity of the atmosphere.[98] Climate is also a principal determinant of an area's fire regime,[99] which refers to the pattern in which fires occur within ecosystems based on factors such as size, severity, and frequency. Studies suggest that most aspects of the fire regime are increasing in the United States (Ch. 6: Forests, KM 1; Ch. 26: Alaska).[18,99,100,101] However, the true extent of an altered fire regime's influence on climate is unclear, because the warming attributable to carbon releases to the atmosphere and decreases in surface albedo (at least temporarily) may be offset by increased reflectivity of the atmosphere from the increased concentration of small particles and the enhanced storage of carbon due to forest regrowth.[99]

Urban regions include several characteristics that can influence climate,[102] including construction materials that absorb more heat than vegetation and soils do, impervious cover that minimizes the cooling effect of evapotranspiration, the canyon-like architecture of buildings that tends to trap heat, and heat generation from vehicle and building emissions.[103,104] These factors make urban areas warmer than their surroundings, a phenomenon referred to as the urban heat island (UHI) effect. Urbanization has a small effect on global temperatures, with more dramatic effects evident regionally where urbanization is extensive.[105,106,107] The local-scale UHI impact is relative to the regional climate such that its effect tends to be more severe in the eastern United States and declines westward.[10,108,109,110,111] Although the evidence is not conclusive, urbanization may also increase downwind precipitation.[112,113,114] Further, climate change may act synergistically with future urbanization (that is, an increase in impervious cover), resulting in increased likelihoods and magnitudes of flood events (e.g., Hamdi et al. 2011, Huong and Pathirana 2013 [115,116]).

Water transport and application to cropland also impact climate. Between 2002 and 2007, irrigated lands expanded by approximately 1.3 million acres in the United States, with much of the change occurring in the Great Plains regions.[117] Approximately 88.5 million acre-feet of water were applied to approximately 55 million acres of irrigated agriculture in the United States in 2012.[118] Globally, the amount of water transported to the atmosphere through irrigated agriculture is roughly equivalent to the amount of water not transported to the atmosphere from deforestation.[119] Studies have shown reductions in surface air temperatures in the vicinity of irrigation due to both evaporation effects[120,121,122] and increases in downwind precipitation as a result of increased atmospheric moisture.[123] These potentially local-to-regional cooling effects are also counterbalanced by constraints on the availability of water for irrigation.[124]

Key Message 2

Climate Impacts on Land and Ecosystems

Climate change affects land use and ecosystems. Climate change is expected to directly and indirectly impact land use and cover by altering disturbance patterns, species distributions, and the suitability of land for specific uses. The composition of the natural and human landscapes, and how society uses the land, affects the ability of the Nation's ecosystems to provide essential goods and services.

Climate can drive changes in land cover and land use in several ways, including changes in the suitability of agriculture (Ch. 10: Ag & Rural),[125,126] increases in fire frequency and extent (Ch. 6: Forests),[18,101] the loss or migration of coastal wetlands,[127] and the spatial relocation of natural vegetation. The extent of the climate influence is often difficult to determine, given that changes occur within interconnected physical and socioeconomic systems, and there is a lack of comprehensive observational evidence to support the development of predictive models, leaving a large degree of uncertainty related to these future changes (Ch. 17: Complex Systems). Models can be used to demonstrate how climate change may impact the production of a given agricultural commodity and/or suggest a change in land use (for example, econometric models, global gridded crop models, and integrated assessment models). However, the true impact may be mitigated by the influence of global economic markets, a shift to a different crop that is better suited to the new climate pattern, technological innovations, policy incentives, or capital improvement projects. This area of integrated, multidisciplinary scientific research is just emerging.

Important feedbacks with agriculture are anticipated under changing climate conditions. Recent trends show a shift from dryland farming to irrigated agriculture throughout much of the Great Plains region (Ch. 22: N. Great Plains; Ch. 23: S. Great Plains).[117] Future projections suggest that cropland suitability may increase at higher latitudes[128] and that croplands could shift to livestock grazing southward.[126] For high-latitude regions, climate change could result in a large-scale transformation from naturally vegetated ecosystems to agronomy-dominated systems. Climate warming also could result in a shift from higher-productivity systems (such as irrigated agriculture) to lower-productivity systems (such as dryland farming).[129] Due to the globally interconnected nature of agricultural systems, climate change has broad implications for food security (Ch. 16: International).[130] Energy policies have also influenced the type and location of agricultural activities; for example, nearly two-thirds of recent land area converted for energy use was due to biofuel expansion[34,131] mandated by the Energy Independence and Security Act of 2007.[30,131] By 2040, the total new land area impacted by energy development could exceed an area the size of Texas—2,700 square miles per year,[34] which is more than two times higher than the historical rate of urbanization.[2]

Natural disturbances such as wildfires can trigger changes in land cover that have the potential to result in a permanent land-cover conversion. Over the past several decades, drought,[132] climate warming, and earlier spring snowmelt have led to an increase in fire activity across the United States (Ch. 6: Forests),[18,133] although the burnt area increase may be partly due to changes in fire suppression policies.[134] Under future warming scenarios (that is, A1B, as described here: http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=3), the burnt area in southwestern California could double by 2050 and increase by 35% in the

Sierra Nevada due to an increase in the length of the fire season and an increase in warmer and drier days.[135] Human activity will continue to play an important role in wildfire frequency and intensity. Hot spots of fire activity were identified at the wildland–urban interface,[136] and urbanization is expected to increase fire hazard exposure to people and property. Land management strategies, such as prescribed burning, fuel reduction and clearing, invasive species management, and forest thinning, have the potential to mitigate wildland fire and its associated consequences,[137] but more research is needed to evaluate their efficacy across a range of spatial and temporal scales.

Current relationships between plant species and climate variables[138] have been used to estimate potential changes in the geographic distribution of species and vegetation under future climate conditions.[12,139,140,141,142,143] Studies have projected the conversion of forests to shrubland and grassland across some areas of the western United States due to increasing aridity, pest outbreaks, and fire, resulting in a substantial transfer of carbon from the biosphere to the atmosphere.[144,145] For example, increases in mountainous forests and grasslands at the expense of alpine and subalpine communities have been projected.[146] Across North America, projected changes include an expansion of tropical dry deciduous forests and desert shrub/scrub biomes, a poleward migration of deciduous and boreal forests, and an expansion of grasslands at the expense of high-latitude taiga and tundra communities.[12,144,146,147,148,149] However, it is important to note that projecting the future distributions of vegetation and land cover is highly complex, driven not only by changes in climate but also land-use changes, shifts in disturbance regimes, interactions between species, and evolutionary changes.[150]

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Traceable Accounts

Process Description

Chapter authors developed the chapter through technical discussions, literature review, and expert deliberation via email and phone discussions. The authors considered feedback from the general public, the National Academies of Sciences, Engineering, and Medicine, and federal agencies. For additional information about the overall process for developing the report, see Appendix 1: Process.

The topic of land-use and land-cover change (LULCC) overlaps with numerous other national sectoral chapters (for example, Ch. 6: Forests; Ch. 10: Ag & Rural; Ch. 11: Urban) and is a fundamental characteristic of all regional chapters in this National Climate Assessment. This national sectoral chapter thus focuses on the dynamic interactions between land change and the climate system. The primary focus is to review our current understanding of land change and climate interactions by examining how land change drives changes in local- to global-scale weather and climate and how, in turn, the climate drives changes in land cover and land use through both biophysical and socioeconomic responses. Where possible, the literature cited in this chapter is specific to changes in the United States.

Key Message 1

Land-Cover Changes Influence Weather and Climate

Changes in land cover continue to impact local- to global-scale weather and climate by altering the flow of energy, water, and greenhouse gases between the land and the atmosphere (*high confidence*). Reforestation can foster localized cooling (*medium confidence*), while in urban areas, continued warming is expected to exacerbate urban heat island effects (*high confidence*).

Description of evidence

The Land-Use and Climate, IDentification of robust impacts (LUCID) project[88,151] evaluated climate response to LULCC using seven coupled land surface models (LSMs) and global climate models (GCMs) to determine effects that were larger than model variability and consistent across all seven models. Results showed significant discrepancies in the effect of LULCC (principally, the conversion of forest to cropland and grassland at temperate and higher latitudes) on near-surface air temperatures; the discrepancies were mainly attributable to the modeling of turbulent flux (sensible heat [the energy required to change temperature] and latent heat [the energy needed to change the phase of a substance, such as from a liquid to a gas]). Land surface models need to be subjected to more rigorous evaluations[151,152] and evaluate more than turbulent fluxes and net ecosystem exchange.[152] Rigorous evaluations should extend to the parameterization of albedo,[153] including the effect of canopy density on the albedo of snow-covered land;[154] the seasonal cycle of albedo related to the extent, timing, and persistence of snow;[155] and the benchmarking of the effect of present-day land cover change on albedo.[156] More recently, there is consistent modeling and empirical evidence that forests tend to be cooler than nearby croplands and grasslands.[91,92,93,95,96,156]

The study of the influence of wildland fire on climate is at its advent and lacks a significant knowledge base.[98,99] Improved understanding would require more research on the detection of fire characteristics;[157] fire emissions;[158] and the relative roles of greenhouse gas (GHG) emissions, aerosol emissions, and surface albedo changes in climate forcing.[98]

The urban heat island (UHI) is perhaps the most unambiguous documentation of anthropogenic modification of climate.[159] Two studies have found that the stunning rate of urbanization in China has led to regional warming,[105,106] which is consistent with the observation that land-use and land-cover changes must be extensive for their effects to be realized.[87] Research on the effects of urbanization on precipitation patterns has not produced consistent results.[113,114] Uncertainties related to the effect of urban areas on precipitation arise from the interactions among the UHI, increased surface roughness (for example, tall buildings), and increased aerosol concentrations.[160] In general, UHIs produce updrafts that lead to enhanced precipitation either in or downwind of urban areas, whereas urban surface roughness and urban aerosol concentrations can either further contribute to or dampen the updrafts that arise from the UHI.[160]

Major uncertainties

Land use and land cover are dynamic; therefore, climate is influenced by a constantly changing land surface. Considerable uncertainties are associated with land-cover and land-use monitoring and projection.[161,162,163,164] Land-cover maps can be derived from remote sensing approaches, but comprehensive approaches are typically characterized by coarse temporal resolution.[2,3,59,60] More recently, remote sensing has enabled annual classification over large areas (national and global), though these efforts have been centered on a single land cover or disturbance type.[68,165,166] Comprehensive multitemporal mapping of land use is even more limited and is a source of considerable uncertainty in understanding land change and feedbacks with the climate system. Deforestation, urbanization, wildland fire, and irrigated agriculture are the main land-use and land-cover changes that influence climate locally and regionally throughout the United States. Deforestation is likely to behave as a warming agent throughout most of the United States, but higher confidence in this finding would require more research on how to treat sensible and latent heat fluxes in coupled GCM–LSM models; the relationship of albedo to forest density in the presence of snow; the timing, persistence, and extent of snow cover; and real-world comparisons of the response of albedo to land-cover change. Urbanization constitutes a continued expansion of the UHI effect, increasing warming at local scales. Determining the effect of urbanization on precipitation patterns and storm tracks would require extensive, additional research. Tabular irrigation water volume estimates, such as those provided by the U.S. Department of Agriculture's (USDA) Farm and Ranch Irrigation Survey, must be translated into maps so that the data can be input in GCMs and LSMs to determine the impact of irrigation on climate. Current translation schemes do not provide consistent model output.[124] The effect of wildland fires on climate processes is an emerging issue for which there is little research. Fire releases carbon dioxide (CO_2) and other GHGs to the atmosphere, which, along with a decreased albedo, should promote warming. These warming effects, however, may be counterbalanced by the release of aerosols to the atmosphere and enhanced carbon sequestration by forest regrowth.[99]

Description of confidence and likelihood

There is *medium confidence* that deforestation throughout much of the continental United States promotes climate warming through a decrease in carbon sequestration and reduced transpiration. There is *low confidence* that wildland fires will impact climate, because many of the associated processes and characteristics produce counteracting effects. There is *high confidence* that urbanization produces local-scale climate change, but there is *low confidence* in its influence on precipitation patterns. There is *high confidence* that surface air temperature is reduced near areas of irrigated agriculture and *medium confidence* that downwind precipitation is increased.

Key Message 2

Climate Impacts on Land and Ecosystems

Climate change affects land use and ecosystems. Climate change is expected to directly and indirectly impact land use and cover by altering disturbance patterns (*medium confidence*), species distributions (*medium confidence*), and the suitability of land for specific uses (*low confidence*). The composition of the natural and human landscapes, and how society uses the land, affects the ability of the Nation's ecosystems to provide essential goods and services (*high confidence*).

Description of evidence

Much of the research assessing the impact of climate change on agriculture has been undertaken as part of the Agricultural Model Intercomparison and Improvement Project (AgMIP),[128] which has been understandably focused on productivity and food security.[128,129,167,168,169] Less effort has been devoted to understanding the impact of climate change on the spatial distribution of agriculture. Deryng et al. (2011)[170] used one of the AgMIP crop models (PEGASUS) to show poleward and westward shifts in areas devoted to corn, soybean, and wheat production. Parker and Abatzoglou (2016)[130] have reported a poleward migration of the USDA's cold hardiness zones as a result of a warming climate. Several empirical studies have found an increase in wildland fires in the western United States over the last several decades,[18,101,171] in which indicators of aridity correlate positively with the amount of area burned. Several studies have reported a decline in forest cover throughout the western United States and project future declines due to a warming climate and increasing aridity, as well as the concomitant likely increase in pest outbreaks and fire.[144,145,172,173,174] Several studies have also reported a poleward shift in the forest communities of the eastern United States, resulting primarily from CO_2 enrichment in a warming and wetter environment.[12,144,147,148,149,175]

Major uncertainties

Determining the impact of climate change on agriculture requires the integration of climate, crop, and economic models,[176] each with its own sources of uncertainty that can propagate through the three models. Sources of uncertainty include the response of crops to the intermingled factors of CO_2 fertilization, temperature, water, and nitrogen availability; species-specific responses; model parameterization; spatial location of irrigated areas; and other factors.[129,169,177] The projection of recent empirical fire–climate relationships[18,101,171] into the future introduces uncertainty, as the empirical results cannot account for future anthropogenic influences (for example, fire suppression management) and vegetation response to future fires.[171,178] Similarly, process-based models

must account for vegetation response to fire, uncertainty in precipitation predictions from climate models, and spatiotemporal nonuniformity in human interactions with fire and vegetation.[178] Many of the studies on climate-induced spatial migration of vegetation are based on dynamic global vegetation models, which are commonly based only on climate and soil inputs. These models aggregate species characteristics that are not uniform across all species represented and are generally lacking ecological processes that would influence a species' range shift.[179,180,181,182,183] Considerable uncertainties are associated with land-cover and land-use monitoring and projection.[161,162,163,164] Land-cover maps can be derived from remote sensing approaches; however, comprehensive approaches are typically characterized by coarse temporal resolution.[2,3,59,60] More recently, remote sensing has enabled annual classification over large areas (at national and global scales), but these efforts have been centered on a single land cover or disturbance type.[68,165,166] Comprehensive multitemporal mapping of land use is even more limited and is a source of considerable uncertainty in understanding land change and feedbacks with the climate system.

Description of confidence and likelihood

There is *high confidence* that climate change will contribute to changes in agricultural land use; however, there is *low confidence* in the direction and magnitude of change due to uncertainties in the capacity to adapt to climate change. There is *high confidence* that climate change will impact urbanization in coastal areas, where sea level rise will continue to have direct effects. There is *medium confidence* that climate change will alter natural disturbance regimes; however, land management activities, such as fire suppression strategies, are likely to be of equal or greater importance. There is *low confidence* that climate change will result in changes to land cover resulting from changes in species distribution environmental suitability.

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6 Forests

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6 Forests

California's multiyear drought killed millions of trees in low-elevation forests.

Key Message 1

Ecological Disturbances and Forest Health

It is very likely that more frequent extreme weather events will increase the frequency and magnitude of severe ecological disturbances, driving rapid (months to years) and often persistent changes in forest structure and function across large landscapes. It is also likely that other changes, resulting from gradual climate change and less severe disturbances, will alter forest productivity and health and the distribution and abundance of species at longer timescales (decades to centuries).

Key Message 2

Ecosystem Services

It is very likely that climate change will decrease the ability of many forest ecosystems to provide important ecosystem services to society. Tree growth and carbon storage are expected to decrease in most locations as a result of higher temperatures, more frequent drought, and increased disturbances. The onset and magnitude of climate change effects on water resources in forest ecosystems will vary but are already occurring in some regions.

Key Message 3

Adaptation

Forest management activities that increase the resilience of U.S. forests to climate change are being implemented, with a broad range of adaptation options for different resources, including applications in planning. The future pace of adaptation will depend on how effectively social, organizational, and economic conditions support implementation.

Executive Summary

Forests on public and private lands provide benefits to the natural environment, as well as economic benefits and ecosystem services to people in the United States and globally. The ability of U.S. forests to continue to provide goods and services is threatened by climate change and associated increases in extreme events and disturbances.[1] For example, severe drought and insect outbreaks have killed hundreds of millions of trees across the United States over the past 20 years,[2] and wildfires have burned at least 3.7 million acres annually in all but 3 years from 2000 to 2016. Recent insect-caused mortality appears to be outside the historical context[3,4] and is likely related to climate change; however, it is unclear if the apparent climate-related increase in fire-caused tree mortality is outside the range of what has been observed over centuries of wildfire occurrence.[5]

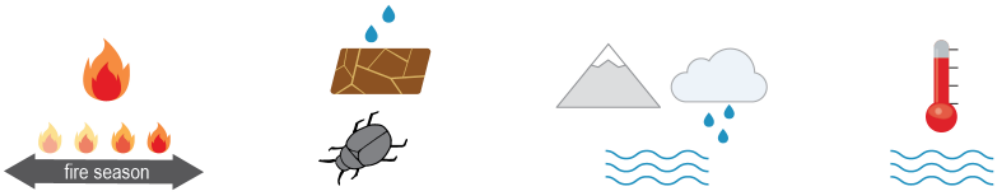
A warmer climate will decrease tree growth in most forests that are water limited (for example, low-elevation ponderosa pine forests) but will likely increase growth in forests that are energy limited (for example, subalpine forests, where long-lasting snowpack and cold temperatures limit the growing season).[6] Drought and extreme high temperatures can cause heat-related stress in vegetation and, in turn, reduce forest productivity and increase mortality.[7,8] The rate of climate warming is likely to influence forest health (that is, the extent to which ecosystem processes are functioning within their range of historic variation)[9] and competition between trees, which will affect the distributions of some species.[10,11]

Large-scale disturbances (over thousands to hundreds of thousands of acres) that cause rapid change (over days to years) and more gradual climate change effects (over decades) will alter the ability of forests to provide ecosystem services, although alterations will vary greatly depending on the tree species and local biophysical conditions. For example, whereas crown fires (forest fires that spread from treetop to treetop) will cause extensive areas of tree mortality in dense, dry forests in the western United States that have not experienced wildfire for several decades, increased fire frequency is expected to facilitate the persistence of sprouting hardwood species such as quaking aspen in western mountains and fire tolerant pine and hardwood species in the eastern United States (see regional chapters for more detail on variation across the United States). Drought, heavy rainfall, altered snowpack, and changing forest conditions are increasing the frequency of low summer streamflow, winter and spring flooding, and low water quality in some locations, with potential negative impacts on aquatic resources and on water supplies for human communities.[12,13]

From 1990 to 2015, U.S. forests sequestered 742 teragrams (Tg) of carbon dioxide (CO_2) per year, offsetting approximately 11% of the Nation's CO_2 emissions.[14] U.S. forests are projected to continue to store carbon but at declining rates, as affected by both land use and lower CO_2 uptake as forests get older.[15,16,17,18] However, carbon accumulation in surface soils (at depths of 0–4 inches) can mitigate the declining carbon sink of U.S. forests if reforestation is routinely implemented at large spatial scales.

Implementation of climate-informed resource planning and management on forestlands has progressed significantly over the past decade. The ability of society and resource management to continue to adapt to climate change will be determined primarily by socioeconomic factors and organizational capacity. A viable forest-based workforce can facilitate timely actions that minimize negative effects of climate change. Ensuring the continuing health of forest ecosystems and, where desired and feasible, keeping forestland in forest cover are key challenges for society.

Climate Change Vulnerabilities and Adaptation Options



Climate Change Vulnerabilities	Increasing wildfire area burned and fire season length	Increasing drought severity and incidence of insect outbreaks	Lower snowpack, increasing precipitation intensity, and higher winter peakflows	Lower summer streamflows and increasing stream temperatures
Adaptation Options	Reduce hazardous fuels with prescribed burning and managed wildfire	Reduce forest stand density to increase tree vigor; plant drought-tolerant species and genotypes	Implement designs for forest road systems that consider increased flooding hazard	Use mapping of projected stream temperatures to set priorities for riparian restoration and coldwater fish conservation

To increase resilience to future stressors and disturbances, examples of adaptation options (risk management) have been developed in response to climate change vulnerabilities in forest ecosystems (risk assessment) in the Pacific Northwest. Vulnerabilities and adaptation options vary among different forest ecosystems. *From Figure 6.7 (Sources: U.S. Forest Service and University of Washington).*

State of the Sector

Forests are distributed across the spectrum of rural to urban environments, covering 896 million acres (including approximately 130 million acres in urban, suburban, and developed areas), or 33% of land in the contiguous United States, Alaska, and Hawai'i. The structure and function of these forests vary considerably across the Nation due to differences in environmental conditions (for example, soil fertility; temperature; and precipitation amount, type, and distribution), historical and contemporary disturbances, and forest management and land-use activities.

Forests on public and private lands provide benefits to the natural environment, as well as economic benefits and ecosystem services (for example, water, fiber and wood products, fish and wildlife habitat, biodiversity, recreational opportunities, spiritual renewal, and carbon storage) to people in the United States and globally. Public forests are mostly managed for non-timber resources or for multiple uses; private lands owned by corporations are mostly managed for timber production, whereas private lands owned by individuals are typically managed for multiple uses. To date, assessments of climate change vulnerability and development of adaptation options in the western United States have occurred mostly on public lands, whereas assessment and adaptation planning and implementation in the eastern United States span public and private lands, with documented examples of adaptation on most ownership types.[19,20] The ability of U.S. forests to continue to provide goods and services is threatened by climate and environmental change and associated increases in extreme weather events and disturbances (for example, drought, wildfire, and insect outbreaks; Figure 6.1), which can pose risks to forest health (that is, the extent to which ecosystem processes are functioning within their natural range of historic variation)[9] and conditions across large landscapes for years to centuries.[1]

The effects of climate change on forests in specific regions are discussed in many of the regional chapters (for example, Ch. 18: Northeast, KM 1 and 2; Ch. 19: Southeast, KM 3 and 4; Ch. 21: Midwest, KM 2; Ch. 24: Northwest, KM 1; Ch. 25: Southwest, KM 2; Ch. 27: Hawai'i & Pacific Islands, KM 2 and 5). Rapid changes have been driven by severe drought in combination with insect outbreaks, which have killed more than 300 million trees in Texas in 2011[21] and more than 129 million trees in California from 2010 to 2017.[22] Also, mountain pine beetles have caused tree mortality across more than 25 million acres in the western United States since 2010, representing almost half of the total area impacted by all bark beetles combined in that region. Recent warming has allowed mountain pine beetles to erupt at elevations and latitudes where winters historically were cold enough to keep them in check.[4,23,24] Wildfire burned at least 3.7 million acres nationwide in 14 of the 17 years from 2000 to 2016—an area larger than the entire state of Connecticut—including a record 10.2 million acres in 2015 (an area greater than Maryland and Delaware combined). Over this same time span, annual federal wildfire suppression expenditures ranged from $809 million to $2.1 billion (Figure 6.4).

Recent insect-caused mortality appears to be far outside what has been documented since Euro-American settlement[3] and is likely related to climate change. It is unclear if the apparent climate-related increase in area burned by wildfire is outside the range of what has been observed over centuries of fire occurrence.[5] Drought, heavy rainfall, altered snowpack, and changing forest conditions are increasing the risk of low summer streamflow, winter flooding, and reduced water quality, with potential negative impacts on aquatic resources and human communities.[12,13] A changing

climate and forest disturbances also interact with chronic stressors (such as fungal pathogens and nonnative species) to affect the scale and magnitude of forest responses to climate change.[25,26]

The ability of society in general and resource managers in particular to adapt to climate change will be determined primarily by socioeconomic factors, technological developments, and organizational capacity (Ch. 28: Adaptation). Although some general principles apply to adaptation (defined here as adjustments in natural systems in response to actual or expected climatic effects that moderate harm or exploit benefits) across all forests, it is biophysical variability, socioeconomic conditions, and organizational objectives that dictate local management approaches. A viable forest-based workforce in local communities can facilitate timely actions that minimize the negative effects of climate change, as long as this workforce can support the objectives of treatments aimed at building forest resilience and provide a justification for treatments (for example, prescribed fire—the purposeful ignition of low-intensity fires in a controlled setting) that help minimize potential economic loss. Reduction in forestland associated with human land-use decisions, especially conversion of forests to nonforests on private lands, is a significant impediment to providing desired ecosystem services from forests. Hence, ensuring the continuing health of forest ecosystems and, where desired and feasible, keeping forestland in forest cover are key challenges for society.

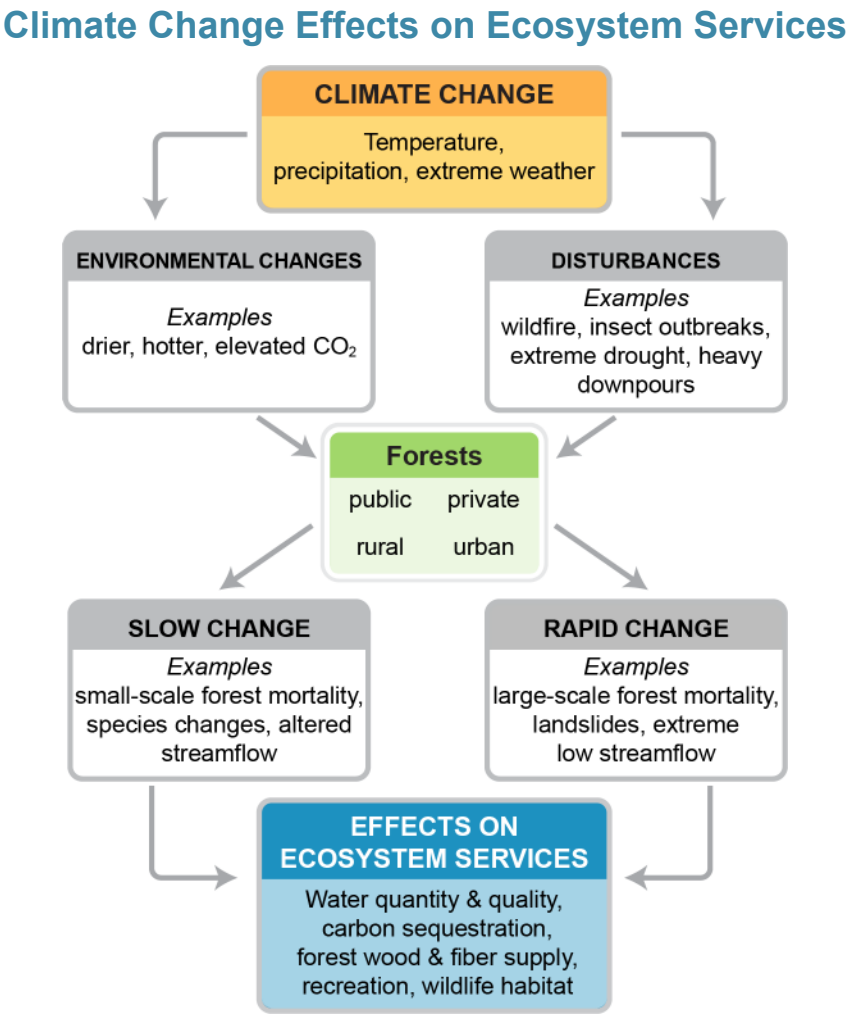


Figure 6.1: Many factors in the biophysical environment interact with climate change to influence forest productivity, structure, and function, ultimately affecting the ecosystem services that forests provide to people in the United States and globally. Source: U.S. Forest Service.

Regional Summary

Forests in the United States vary in their susceptibility to climate change due to differences in biophysical conditions and anticipated changes in future climate (see regional chapters for specific discussions). For example, eastern forests are largely expected to undergo gradual change, punctuated by rapid changes from small-scale disturbances.[26] Across most U.S. forests, an increased frequency of large-scale disturbances is expected to be the primary challenge to maintaining healthy, functional forest ecosystems in a warmer climate; however, forest disturbances resulting from human activity can add to the effects of climate in some parts of the United States.[27] Over the past decade, several large-scale disturbances have killed hundreds of millions of trees at different locations in the United States. The two Case Studies in this chapter illustrate how disturbances can cause rapid changes in the ecology and structure of forests that can result in significant social and economic effects.

Case Study: Large-Scale Tree Mortality in the Sierra Nevada

Five years of consecutive drought ended in California in 2017, with 2015 being the hottest and driest year in the historical record (since the late 1800s). The drought weakened trees and enabled extensive bark beetle outbreaks, which killed 40 million trees across 7.7 million acres of Sierra Nevada forests through 2015. Annual tree mortality increased by an order of magnitude to thousands of dead trees per square mile during this period.[28] The winters 2015–2016 and 2016–2017 brought significant precipitation to much of California, but drought stress remained high in many areas. An additional 62 million trees died in 2016, and 27 million trees died in 2017, bringing the total to at least 129 million trees since 2010.[22] Mortality was most severe at lower elevations, on southwest- and west-facing slopes, and in areas with shallow soils.[29]

Tree Mortality at Bass Lake Recreation Area

Figure 6.2: A five-year drought in California (2011–2016) led to western pine beetle outbreaks, which contributed to the mortality of 129 million trees. As a result, the structure and function of these forests are changing rapidly. Prolonged droughts are expected to become more common as the climate continues to warm, increasing stress on lower-elevation tree species. Photo credit: Marc Meyer, U.S. Forest Service.

This level of tree mortality in the Sierra Nevada is unprecedented in recorded history.[30,31] In some of the most heavily impacted areas, 70% of trees died in a single year (Figure 6.2). Much of this mortality was attributed to the western pine beetle colonizing ponderosa pine, but other tree and shrub species were also affected. Some forests once dominated by ponderosa pine are now dominated by incense cedar. This change in stand structure and composition has increased the likelihood of high-intensity surface fires and large wildfires.[31] In general, widespread tree mortality can alter local hydrology (with more water availability but also higher peak flows) and negatively affect ecosystem services (for example, decreased timber supply and decreased recreation opportunities), effects that will persist for many years.[2,32,33]

Case Study: Increased Wildfire Risk in the Southeastern United States

Southeastern landscapes are dominated by private lands and relatively high human populations, so changes in social behavior (for example, human-caused fire ignitions), policy (for example, fire suppression), and climate can affect wildfire activity.[27] Modeling studies suggest that the southeastern United States will experience increased fire risk and a longer fire season.[34,35] Although projections vary by state and ecoregion,[36] on average, the annual area burned by lightning-ignited wildfire is expected to increase by at least 30% by 2060, whereas human-ignited wildfire is expected to decrease slightly due to changes in factors driving human-ignited wildfire, including projected losses of forestland and increased efforts to suppress and prevent wildfires. Although native vegetation is well-adapted to periodic wildfire, most people living near wildlands are not. More frequent and larger wildfires, combined with increasing development at the wildland–urban interface (where people live in and near forested areas), portend increasing risks to property and human life. For example, a prolonged dry period in the southern Appalachian region in 2016 resulted in widespread wildfires that caused 15 deaths and damaged or destroyed nearly 2,500 structures in Gatlinburg, Tennessee (Figure 6.3). In a warmer climate, increased fire frequency will damage local economies and degrade air quality in the Southeast.

Fire Damage in Gatlinburg, Tennessee

Figure 6.3: In autumn 2016, a prolonged dry period and arson in the southern Appalachian region resulted in 50 major wildfires that burned over 100,000 acres in 8 states, caused 15 deaths, and damaged or destroyed nearly 2,500 structures in Gatlinburg, Tennessee. If drought or prolonged dry periods increase in this region as expected, fire risk will increase in both forests and local communities. Photo credit: Flickr user highlander411 (CC BY 2.0).

Key Message 1

Ecological Disturbances and Forest Health

It is very likely that more frequent extreme weather events will increase the frequency and magnitude of severe ecological disturbances, driving rapid (months to years) and often persistent changes in forest structure and function across large landscapes. It is also likely that other changes, resulting from gradual climate change and less severe disturbances, will alter forest productivity and health and the distribution and abundance of species at longer timescales (decades to centuries).

Rapid Forest Change—Wildfire

Most fire-prone forests (forests that are likely to burn at least once every few decades) have the ability to persist as more fires occur, but the resilience of these ecosystems depends on three factors: 1) continued presence of fire-adapted species, 2) fire intensity (the amount of heat energy released) and frequency of future fires, and 3) societal responses to increased fires. A century of fire exclusion in fire-prone forest ecosystems in the United States (especially lower-elevation ponderosa pine forests and mixed conifer forests in dry locations in the West) has created landscapes of dense forests with high flammability and heavy surface and canopy fuel loads (combustible dead and live vegetation).[37] Over the past 20 years, a warm, dry climate has increased the area burned across the Nation.[38] Large, intense wildfires in some locations[39] (Figure 6.4) have been difficult to suppress, increasing risk to property and lives, including those of firefighters.[40,41] The cost of fire suppression has also increased over time, partially driven by the high cost of protecting property in the wildland–urban interface.[42,43]

Wildfires—Changes in Area Burned and Cost

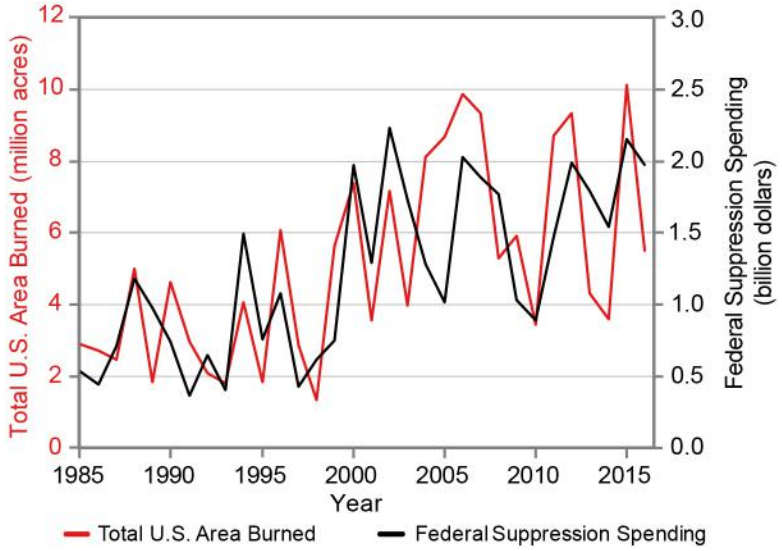


Figure 6.4: This figure shows the annual wildfire area burned in the United States (red) and the annual federal wildfire suppression expenditures (black), scaled to constant 2016 U.S. dollars (Consumer Price Index deflated). Trends for both area burned and wildfire suppression costs indicate about a fourfold increase over a 30-year period. Source: U.S. Forest Service.

The duration of the season during which wildfires occur has increased throughout the western United States as a result of increased temperatures[44,45] and earlier snowmelt.[46,47] Increased vapor pressure deficit (Ch. 21: Midwest, Figure 21.3)[48] and reduced summer precipitation[49] have deepened summer droughts in the West and thus increased wildfire risk.[50] By the middle of this century, the annual area burned in the western United States could increase 2–6 times from the present, depending on the geographic area, ecosystem, and local climate.[51,52] An increase in the area burned, however, does not necessarily translate to negative impacts to ecosystems (Figure 6.5). As the spatial extent of wildfires increases, previously burned areas will in some cases provide fuel breaks that influence the pattern, extent, and severity (the degree to which fire causes vegetation damage and mortality) of future fires.[53] Future wildfire regimes will be determined not only by climate but also by topography, fuel accumulation (as affected by plant growth and frequency of disturbances), and efforts to suppress and prevent fires.[54,55]

Wildfire risk can be reduced in low-elevation, dry conifer forests in the West and conifer forests in the South by reducing stand density (thinning), using prescribed burning, and letting some fires burn if they will not affect people. Frequent prescribed burning in fire-prone and fire-dependent (forests that require fire to maintain structure and function) southern forests has been a socially accepted practice for decades, illustrating how wildfire risk can be reduced. However, health risks from smoke produced by prescribed burning are a growing concern in the wildland–urban interface (see Ch. 19: Southeast for additional discussion about fire in the southeastern United States and Ch. 13: Air Quality, KM 2 on the effects of wildfires on health).[56]

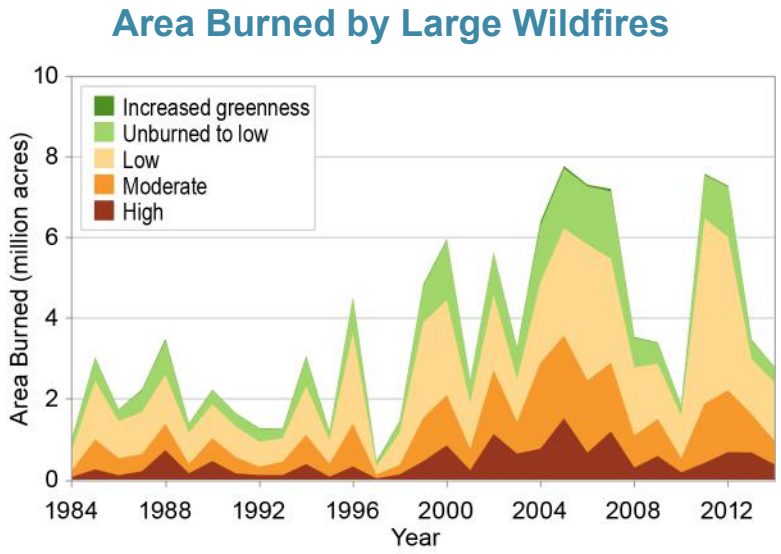


Figure 6.5: This figure illustrates the area burned by large wildfires (greater than 1,000 acres in the western United States and greater than 500 acres in the eastern United States) for 1984–2014. Although the area with moderate-to-high burn severity (amount of fire damage to the forest canopy) has increased in recent decades, it has not changed as a proportion of the total area burned (severity does vary across regions). Increases in the areas of severely burned forests will have implications for ecosystem processes, such as tree regeneration[57,58,59] and ecosystem services, including timber production, water quality, and recreation. Source: redrawn from EPA 2016.[60]

Rapid Forest Change—Insects and Pathogens

Climate change is expected to increase the effects of some insect species in U.S. forests[23,61,62] but reduce the effects of others.[63] For example, drought increases populations of some defoliating insect species[64] but decreases populations of other defoliators.[65] In some cases, fire exclusion in fire-prone forests has exacerbated the effects of insects by increasing forest density, thus reducing tree vigor (the capacity of a tree to resist stress) and resistance to insect attack.[3] Higher damage from native insects on trees with reduced vigor is expected to be one of the biggest effects of a warmer climate. Altered thermal conditions, including varying temporal patterns, will disrupt some insect life cycles, causing seasonal mismatches between insect species and tree hosts in some systems.[66]

Over the past 30 years, tree mortality caused by bark beetles in the western United States has exceeded tree mortality caused by wildfire,[2] raising concerns about the sustainability of some western forests to provide ecological goods and services over time.[67,68] Bark beetle epidemics in forests with commercially valuable tree species can negatively affect timber prices and the economic well-being of forest landowners and wood processors.[69] Many bark beetle outbreaks have been associated with drought and elevated temperature.[23,63] Recently, western pine beetles contributed to the mortality of 129 million trees weakened by a period of severe drought in California (see Case Study "Large-Scale Tree Mortality"). The southern pine beetle is the only bark beetle species in the eastern United States that causes extensive tree mortality. Although little evidence exists for drought-caused outbreaks of this beetle,[63] a recent increase in its range into the northeastern United States, facilitated by increasing winter temperatures, now threatens pine barrens in New York and Massachusetts.[70]

The northward expansion of the hemlock woolly adelgid, a nonnative species that attacks eastern hemlock, has been facilitated by higher minimum winter temperatures.[71] Similarly, the range of mountain pine beetles is expanding with warming; new breeding populations are now found in parts of the western plains and in jack pine in boreal forests in Alberta, Canada.[24,72,73] Mountain pine beetle populations are also expanding in high-elevation forests of the western United States, affecting whitebark pine and other high-elevation pine species.[4,23] Whitebark pine serves as a keystone species that quickly establishes after a disturbance and provides critical food sources for birds and mammals. Whitebark pine is expected to suffer significant mortality in the future due to the combined effects of white pine blister rust, mountain pine beetles, and a warmer climate.[74]

Fungal pathogens, especially those that depend on stressed plant hosts for colonization, are expected to perform better and have greater effects on forests as a result of climate change.[63,75,76] For example, increasing annual temperatures and precipitation in portions of New England have provided ideal conditions for outbreaks of leaf diseases in eastern white pine,[77] whereas the effects of some pathogens directly affected by climate (such as needle blights) are typically reduced in areas with decreased precipitation.[75] Timing of pathogen life cycles relative to seasonal changes in temperature and precipitation will be critical in determining where and how damage might change.

Insect and disease outbreaks often interact with other disturbances, compounding their potential effects on ecosystem services. For example, in lodgepole pine forests attacked by mountain pine beetles, the intensity of surface and crown fires increases in stands impacted by outbreaks, but typically for less than 10 years (e.g., Page and Jenkins 2007, Hicke et

al. 2012, Jenkins et al. 2014[78,79,80]). Beetles have minimal effects on fire severity in some locations due to variability in topography, fuels, and fire weather.[81] A recent study in California in areas heavily affected by drought and western pine beetles (see Case Study "Large-Scale Tree Mortality") reported a greater potential for large-scale wildfires driven by the amount and continuity of combustible woody material from dying trees.[31]

Long-Term Forest Change

Forests that frequently run out of water stored in the soil during the growing season are considered water limited, whereas forests where the growing season length or productivity rate is limited by snowpack and cool temperatures are considered energy limited. A warmer climate will generally decrease tree growth in water-limited forests (many semiarid and low-elevation forests in the western United States) but may increase growth in some energy-limited forests (the majority of forests in the eastern United States and coastal Alaska and high-mountain forests with short growing seasons).[6,82] Experimental evidence shows that elevated atmospheric carbon dioxide (CO_2) can increase tree growth (especially where soil nutrients are adequate), but it is uncertain whether this increase will occur in mature forests or will continue as younger forests age.[83] Positive effects of CO_2 on growth will be negated in some species and locations (such as near urban areas) by air pollutants such as ground-level ozone (not the protective layer of ozone high in the atmosphere), where concentrations of those pollutants are high enough to cause toxic effects in plants.[84] Drought and extreme temperatures can cause heat-related stress in vegetation, in turn reducing forest productivity and reducing tree vigor.[7,8] Although the effects are complex and variable among forests, warming and elevated CO_2 can also impact below-ground processes, such as nitrogen and carbon cycling,[85] with feedbacks that may impact forest productivity.[86]

The direct effects of climate change on tree mortality and forest health will likely be obscured by the slow response times of long-lived tree species.[87] In some cases, climate-related stresses weaken trees, predisposing them to additional stresses.[88] Variability in the drought response of tree species (for example, due to differences in hydraulic characteristics) is expected to influence how some forests deal with water stress.[89] A lagged response and variability among species can make it difficult to attribute growth reductions to episodic drought, and growth reductions can persist for years.[7,90,91] For species in which seed crops depend on resources stored over several growing seasons, reproductive responses are likely to lag behind climatic variation.[92]

The rate of climate warming will influence the rate and magnitude of potential changes in forest health, competition for resources among tree species, structure, and function, affecting the growth and distribution of some tree species.[10,11] Negative effects on some species can benefit other species, and reorganization and changes in the structure of forest communities depend on the capacity of locally adapted populations to occupy new areas that become suitable as a result of climate change. For example, warming in the coastal region of the southern United States may result in the replacement of salt grass with mangrove forests (see Ch. 19: Southeast for additional information on mangrove forests).[93]

Canopy phenology (seasonal patterns of leaf emergence and flowering) responds to annual-to-decadal variation in climate,[94,95] and evidence exists that changes in canopy phenology are contributing to altered species ranges and potential increases in water and nutrient limitations.[96] Some studies report shifts in

elevation ranges of terrestrial plant species in general,[97,98,99] whereas many of the studies that focus on tree species do not.[100,101,102,103] If large-scale latitudinal shifts in tree distributions are occurring, they are ambiguous at present;[10,104] however, some evidence suggests that some boreal species are shifting poleward as reproduction fails on the southern edge of their range.[105]

Key Message 2

Ecosystem Services

It is very likely that climate change will decrease the ability of many forest ecosystems to provide important ecosystem services to society. Tree growth and carbon storage are expected to decrease in most locations as a result of higher temperatures, more frequent drought, and increased disturbances. The onset and magnitude of climate change effects on water resources in forest ecosystems will vary but are already occurring in some regions.

The Millennium Ecosystem Assessment[106] defines four categories of ecosystem services: supporting, provisioning, regulating, and cultural. Recent studies have focused on defining and quantifying the full range of services provided by forests including recreation, wildlife habitat, biodiversity, cultural values, and non-timber forest products.[107,108] Here, we focus on climate change effects on two of the most important forest-based services: forest carbon dynamics (regulating and provisioning) and forest water resources (regulating and provisioning). (For additional discussion on the effects of climate on ecosystem services, see Ch. 7: Ecosystems and the regional chapters.)

Forest Carbon Dynamics

Forest productivity (Key Message 1) is one of many factors that determine carbon storage potential.[109] Typically, soil carbon is the largest and most stable carbon pool in forest ecosystems,[14,110,111,112] but increased above-ground biomass production in forests is not necessarily accompanied by higher soil carbon content. In some locations, heavy rainfall events will result in flood-related tree mortality, leading to soil erosion and losses of particulate and dissolved organic carbon from forests.[113] Increased disturbances such as harvesting, wildfire, and insect and disease damage can also release carbon stored in soils, especially where multiple disturbances occur over a short time span (Figure 6.6).[114]

The fate of carbon in forests depends, in large part, on the type, extent, frequency, and severity of the disturbance.[114,115] Severe disturbances, such as stand-replacing wildfire, typically result in the immediate release of carbon to the atmosphere,[32] a reduction in stand productivity, the transfer of carbon from live to dead pools, and an increase in decomposition.[114,115] Productivity will gradually increase following a disturbance, and decomposition will decrease as the forest recovers. The abrupt release of carbon after a disturbance transitions to net carbon uptake through forest regrowth. However, the full effect of the disturbance on atmospheric CO_2 depends on the timing of disturbance-induced CO_2 releases. Although carbon storage in biomass will increase in areas where tree growth rates rise, those increases will be small compared to the reduced storage that occurs in response to more disturbances.[18]

Forest Disturbances Across the United States

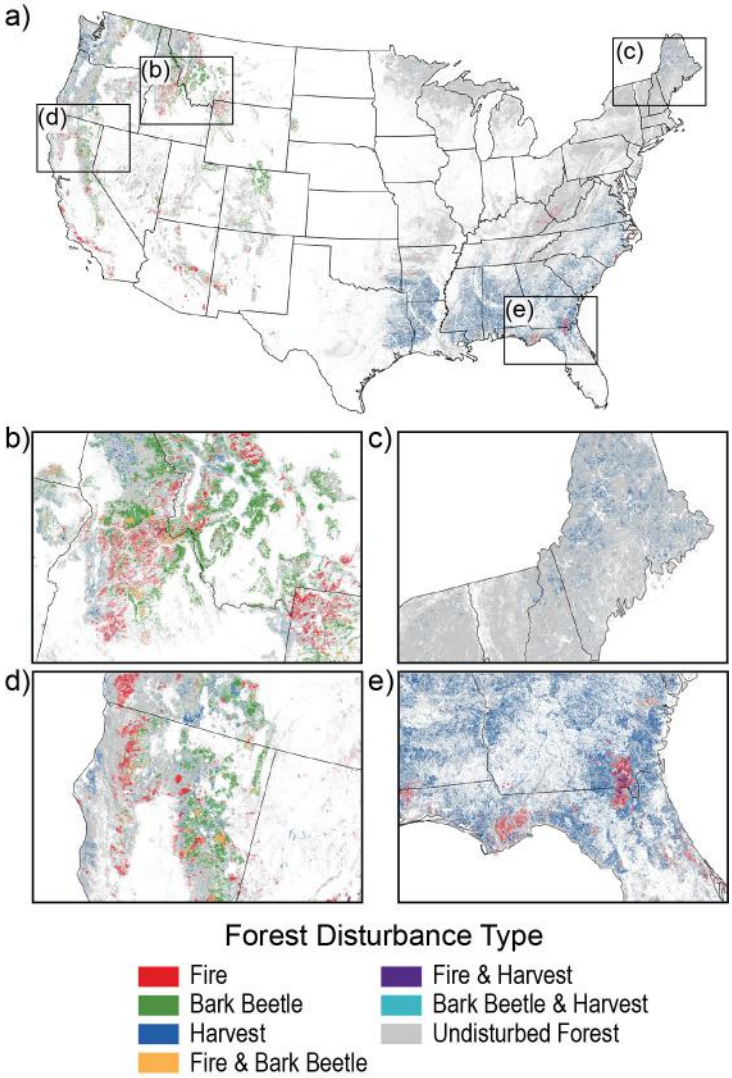


Figure 6.6: This figure shows the cumulative area of disturbed forestland across the contiguous United States for 1984–2014. The small boxes illustrate how disturbances differ regionally. Data for Alaska, Hawai'i and the U.S.-Affiliated Pacific Islands, and the U.S. Caribbean regions were not shown on the original map from the published source. Source: adapted from Williams et al. 2016.[114]

Economic and population growth will affect land-use decisions that influence forest-based carbon storage. Over the last several decades, conversion of forestland to other land uses has contributed to CO_2 emissions,[14,116] and this trend is likely to continue, although this is among the most significant sources of uncertainty in the forest carbon sink in the United States.[18,117,118] The current (2017) U.S. deforestation rate (the conversion from forest to nonforest land use) of 0.12% per year is more than offset by forest gain from afforestation (the establishment of a forest where there was no previous tree cover) and reforestation, for a net gain of forest area of 0.09% per year (679,000 acres).[14] Gains occur mostly through a transition from grasslands and croplands to shrublands, woodlands, and forests, and losses occur mostly in urban areas (see Ch. 5: Land Changes for details on forest land-use trends).[14] While some individual states have lost forestland, overall, each region of the United States (for example, northern, southern, Rocky Mountain, and Pacific coast) has gained forestland area over the past 20 years.[14,16]

Net storage of atmospheric carbon by forests (742 teragrams, or Tg, of CO_2 per year from 1990 to 2015) has offset approximately 11% of U.S. CO_2 emissions.[14] Assuming no policy intervention—and accounting for land-use change, management, disturbance, and forest aging—U.S. forests are projected to continue to store carbon but at declining rates (35% less than 2013 levels by 2037) as a result of both land use and lower CO_2 uptake as forests grow older.[15,16,17,18,42]

Although forest area has increased over the last few decades (Ch. 5: Land Changes, Figure 5.1), this trend is projected to level off by 2030, then decline gradually as human population expands and afforestation on agricultural lands slows,[18,42] with more rapid leveling in the West compared to the East. However, carbon accumulation in surface soils (at depths of 0–4 inches) resulting from reforestation activities can help mitigate declining carbon storage in U.S. forests over the long term. Surface soils in reforested areas are currently accumulating 13–21 Tg carbon per year, with the potential to accumulate hundreds more Tg of carbon within a century.[112,119]

Economic and population trends will affect national and global production and consumption of wood products, which can temporarily store carbon. The storage of carbon in and emissions from wood products contribute to carbon stores and exchanges with the atmosphere; the carbon stored in wood products accumulates as wood is harvested from forests at a rate that exceeds carbon releases from the decay and combustion of wood products already in use. The harvested wood products pool alone is not a direct sink for atmospheric carbon, but losses from the pool are a direct source of atmospheric carbon. Although the contribution of harvested wood products is uncertain, the worldwide net surplus of carbon in wood products is estimated to be approximately 8% of the established global forest sink (189 Tg carbon per year).[120] In the United States, 76% of the annual domestic harvest input to the wood products pool in 2015 (110 Tg carbon per year) was offset by release processes (84 Tg carbon per year), resulting in an increase in wood products of 26 Tg carbon.[14]

Forest Water Resources

Forested watersheds provide water for municipal water supplies, agricultural irrigation, recreation, spiritual values, and in-stream flows for aquatic ecosystems. Changes in snowfall amount, timing, and melt dynamics are affecting water availability and stream water quality. In the western United States (especially the Pacific Northwest), less precipitation is falling as snow and more as rain in winter months, leading to a longer and drier summer season (Ch. 24: Northwest).[121] Persistence of winter snowpacks has also decreased in the northeastern United States over the last few decades, with more mid-winter thaws (Ch. 18: Northeast). Changing snowmelt patterns are likely to alter snowmelt contributions to the flushing of soil nutrients into streams in both western[122] and eastern forests.[123]

Forest watersheds moderate the effects of extreme climate events such as drought and heavy rainfall, thus minimizing downstream impacts on aquatic ecosystems and human communities such as flooding, low flows, and reduced water quality. Disturbances and periodic droughts affect streamflow and water quality,[12,13,124] as do changes in forest structure that are influenced by climatic variability and change, such as leaf area and species distribution and abundance.[33] For example, drought-related bark beetle outbreaks and wildfire kill trees, reducing water uptake and evapotranspiration and potentially increasing water yield,[125] although water yield can decrease if regrowing species have higher water-use demands than did the insect- or fire-killed trees.[126]

Wildfires can also increase forest openness by killing midstory and overstory trees, which promotes earlier snowmelt from increased solar radiation. This, in turn, leads to more winter runoff and exacerbates dry summer conditions, especially in cooler interior mountains.[127,128] In warmer forests, typically in wetter climates where wildfire is currently rare, increased forest openness can in some cases increase snowpack retention.[129] Wildfires can increase erosion and sediment in western U.S. rivers,[130] as well as reduce tree cover adjacent to rivers and streams and thus increase stream temperature.[131,132] In eastern U.S. forests, the proportion of tree species with moderate water demands (mesophytes) is increasing in many areas as a result of fire exclusion, less logging and other disturbances, and possibly a warmer climate.[133,134] Mesophytes transpire more water than other species occupying the same area, thus reducing streamflow.[135,136]

Key Message 3

Adaptation

Forest management activities that increase the resilience of U.S. forests to climate change are being implemented, with a broad range of adaptation options for different resources, including applications in planning. The future pace of adaptation will depend on how effectively social, organizational, and economic conditions support implementation.

Decisions about how to address climate change in the context of forest management need to be informed by a better understanding of the risks of potential climate change effects on natural resources and the organizations that manage those resources. For example, risks posed by ecological disturbances can be reduced by first assessing specific disturbance components (such as wildfire exposure) and second identifying forest management activities that can be implemented to reduce risk.[52] However, identifying how climate change will alter biophysical conditions (risk assessment) and how forest management organizations will respond to future changes (risk management) is complex. Describing operational (technical and financial), economic, and political risks is even more difficult. Furthermore, identifying interactions among all types of risks at regional and local scales will provide land managers with the information needed to manage forests sustainably across large landscapes (Ch. 28: Adaptation).[137] To that end, recent nationwide projects examining site-specific adaptation practices help inform forest management focused on maintaining long-term productivity under future climatic conditions.[20,138,139]

Assessments of climate change effects and adaptation actions are being incorporated into resource management plans, environmental assessments, and monitoring programs of public agencies.[42,140] Adaptation planning tools and compendia of adaptation options for forest resources are now institutionalized in public land management in much of the United States (Ch. 28: Adaptation).[19,141] Adaptation actions are also being implemented by Native American tribes and communities, with an emphasis on culturally significant forest resources, such as flora and fauna, which in turn affect sovereignty and economic sustainability.[142] Adaptation is especially urgent for Native American communities affiliated with reservations where place-based traditional medicine, ceremonial practices, and methods of gathering and hunting for food contribute to cultural identity (Ch. 15: Tribes).[143]

Implementing climate change adaptation measures in forest management requires an understanding of the effects of climate change on different types of forests, forest-related

Climate Change Vulnerabilities and Adaptation Options

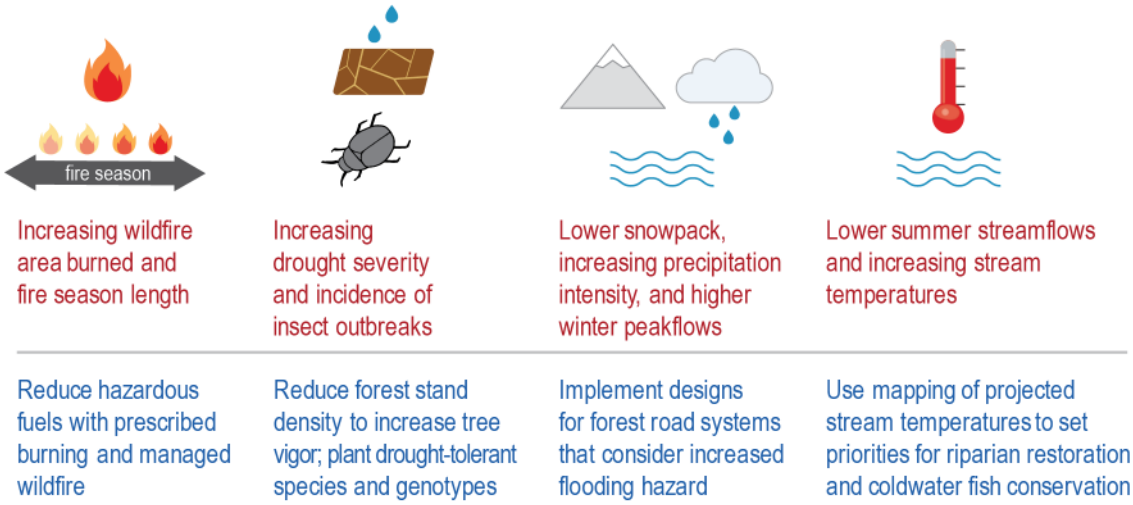


Figure 6.7: To increase resilience to future stressors and disturbances, examples of adaptation options (risk management) have been developed in response to climate change vulnerabilities in forest ecosystems (risk assessment) in the Pacific Northwest. Vulnerabilities and adaptation options vary among different forest ecosystems. Sources: U.S. Forest Service; University of Washington.

enterprises, and resource-dependent communities (Figure 6.7). However, even if the potential magnitude and consequences of climate change are well understood and viable management responses exist, adaptation measures cannot occur unless management organizations (on public and private lands) have the capacity (people and financial resources, enabled by policy) to implement management responses.[144]

Fortunately, many ongoing practices that address existing forest management needs—stand density management, surface fuel reduction, control of invasive species, and aquatic habitat restoration—contribute to the goal of increasing resilience to higher temperatures, drought, and disturbances.[127,144,145,146,147] Fuel treatments across large landscapes have the additional benefit of creating defensible space for fire suppression, especially near the wildland–urban interface. Resource managers are evaluating how these practices can be modified and implemented to address future climate risks.[141] For example, forest managers in dry western U.S. forests are considering greater reductions in stand density to increase forest resistance and resilience to fire, insects, and drought.[148] Implementation of these practices can be costly, often confront legal and administrative barriers,[149] and must consider economic tradeoffs associated with management of other natural resources.[55]

Applications of these and other practices vary as a function of ownership objectives, timber and non-timber wood product markets, policy constraints, and setting (urban, rural, or wildland–urban interface). For example, land managers in regions where short-rotation, plantation management of forest tree species is common (for example, private lands in the southern United States and Pacific Northwest) have the flexibility to periodically shift species and genetic composition of trees to align with future changes in climate and disturbance regimes.[150] A significant amount of adaptation has occurred on public lands, including actions that reduce climate-related risks to water resources such as 1) design of sustainable forest road systems that take into account increased flooding hazard, including upsizing culverts to match projected streamflows; 2) joint planning and design of fuel treatments

(including prescribed burning) and watershed restoration to create resilient terrestrial and aquatic ecosystems;[127] 3) comprehensive mapping of projected stream temperatures to set priorities for riparian restoration and cold-water fish conservation;[151] and 4) supporting viable American beaver populations to facilitate retention of cool water in forested aquatic systems (Figure 6.8).[140]

Applying climate change adaptation management activities over large areas of forestland will be challenged by projected declines in the size of the forest sector workforce and receding timber product outputs in some parts of the country.[42] Declines in the workforce mean fewer skilled workers who can carry out management actions, although collaborative efforts by nongovernmental organizations are emerging to assist with climate change adaptation.[152] Low timber product output, the result of abundant supplies of timber and low demand for primary and secondary timber products,[153] means lower prices for timber, which have trended downward since the late 1990s (e.g., Timber Mart-South 2018[154]), thereby providing fewer opportunities to offset treatment costs with sales of timber removed. As a result, weak timber markets mean reduced incentives for private forest owners to actively manage forests in ways that enhance climate resilience. However, multiorganization collaboration, widespread availability of adaptation options,[155,156] and a growing list of examples of on-the-ground implementation bode well for the future of climate-informed forest management. Flexible management approaches that promote learning and sharing among interested parties can help accelerate implementation.

Reintroducing Beavers to Build Climate Resilience

Figure 6.8: Engineering by beavers encourages the slow release of water to downstream users and keeps water cool for migrating salmon and other aquatic species. Reintroduction of beavers throughout the western United States is helping to retain these functions in forested watersheds, increasing resilience to a warmer climate and reduced snowpack in mountains. Photo credit: Sarah Koenigsberg, courtesy of The Beaver Believers.

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California forest: Nathan Stephenson, U.S. Geological Survey.

Traceable Accounts

Process Description

Lead authors, chapter authors, and technical contributors engaged in multiple technical discussions via teleconference between September 2016 and March 2018, which included a review of technical inputs provided by the public and a broad range of published literature as well as professional judgment. Discussions were followed by expert deliberation on draft Key Messages by the authors and targeted consultation with additional experts by the authors and technical contributors. A public engagement webinar on May 11, 2017, solicited additional feedback on the report outline. Webinar attendees provided comments and suggestions online and through follow-up emails. Strong emphasis was placed on recent findings reported in the scientific literature and relevance to specific applications in the management of forest resources.

Key Message 1

Ecological Disturbances and Forest Health

It is very likely that more frequent extreme weather events will increase the frequency and magnitude of severe ecological disturbances, driving rapid (months to years) and often persistent changes in forest structure and function across large landscapes (*high confidence*). It is also likely that other changes, resulting from gradual climate change and less severe disturbances, will alter forest productivity and health and the distribution and abundance of species at longer timescales (decades to centuries; *medium confidence*).

Description of evidence base

Many ecological responses to climate change in U.S. forests are mediated though disturbance, because the occurrence and magnitude of most major forest disturbances are sensitive to subtle changes in climate.[1] Published literature since the Third National Climate Assessment (NCA3) continues to show an increase in the frequency of large (thousands to hundreds of thousands of acres) ecological disturbances in forests across the United States. There is strong evidence that these changes, in combination with accumulated fuels, have resulted in larger wildfires in recent years (the past 10 to 20 years),[2,38,39] making them harder to suppress and increasing human health and safety concerns for nearby communities[40] and wildland firefighters.[157] Fire suppression costs continue to increase in response to larger fires and an expanding wildland–urban interface.

Although the increasing size and costs of fighting wildfires are known with high certainty,[158] short- and long-term effects on forests vary according to the ability of tree species to survive or regenerate after wildfire.[159] Future fire regimes and their impacts on U.S. forests will be governed by climate as well as topography, ecosystem productivity, and vegetation adaptations to fire. For example, altered distribution and abundance of dominant plant species may affect the frequency and extent of future wildfires (Ch. 29: Mitigation). The potential of an area to reburn (that is, burn again after experiencing a previous fire) will depend on how the previous fire was suppressed, the severity of that fire, how rapidly fuel accumulated after the fire, and postfire management activities.[53] These variables create uncertainty in predicting the spatial distribution, number, and sizes of wildfires in future decades.

The published literature contains strong evidence that insects are causing rapid changes in forest structure and function across large landscapes. Causal factors are primarily elevated temperatures, droughts, and water stress, which exert indirect effects mediated through host tree species and direct effects on insects. For example, in western North America, several species of bark beetles have had notable outbreaks over the past 30 years, and some have exceeded the spatial extent of what has been previously documented, affecting ecosystem services at broad spatial scales.[3] The spatial extent of recent outbreaks of mountain pine beetles represents an area larger than the 11 smallest U.S. states combined, and insect outbreak models project increased probabilities of mountain pine beetle population success in the future.[23] In addition, evidence suggests that climate change is expanding the range of bark beetles in both the western and eastern United States,[66,70,71] caused by higher minimum temperatures associated with climate change. For example, whitebark pine is expected to suffer significant mortality in future decades due to the combined effects of white pine blister rust, mountain pine beetles, and climate change.[74]

The magnitude and direction of defoliator responses to climate change vary, limiting our ability to project the effects of climate change[69] and preventing generalizations about climate-related effects on defoliators, despite their importance throughout the United States. Fungal pathogens that depend on stressed plant hosts for colonization are expected to perform better and have greater impacts on forests.[63,75,76] In contrast, some pathogens directly affected by moisture availability (for example, needle blights) are expected to have reduced impact.[75]

Mounting evidence suggests that some bird and insect populations show changes in distribution that align with temperature increases in recent decades (Ch. 7: Ecosystems).[160,161,162,163] These species groups are characterized by short generation times, high mobility, or both. Some evidence suggests that the rate of climate change is outpacing the capacity of trees and forests to adjust, placing long-lived tree populations at risk. Species distribution models concur that climate change can affect suitable habitat,[11] although it is unclear if these effects are translating into species range shifts. Some studies report shifts in elevation ranges,[97,98] whereas others do not.[100,101,103] In summary, evidence indicates substantial effects of climate change on forest health but varied capacity for tree species to relocate as conditions change.

Understanding and predicting the effects of climate change on forests are obscured by the slow response times of long-lived trees.[87] Increasing evidence suggests that climate-related stresses weaken trees, predisposing them to additional stresses that take many years to be observed,[88] and that growth reductions following drought can persist for years.[7,90,91] For species in which seed crops depend on resources stored over several growing seasons, it is likely that reproductive responses will lag behind climate variation.[92] Recent studies in the eastern United States suggest that changes in tree species composition (such as an increased proportion of mesophytes) over the past few decades in some forests are contributing to lower streamflow[136] and increased vulnerability of forests to drought.[164] Warming temperatures and changing precipitation are altering leaf phenology (for example, earlier spring leaf-out and later leaf fall) in some areas, which is likely to affect forest carbon and water cycling.[95,165]

Major uncertainties

Although wildfire frequency and extent are very likely to increase in a warmer climate, spatial and temporal patterns of fire are difficult to project, especially at smaller than regional scales. The

effects of a warmer climate are well known for some insect species (such as bark beetles), but the effects of long-term thermal changes on most insect species and their community associates are uncertain. Scientific information on the effects of climate change on fungal pathogens is sparse, making projections of forest diseases uncertain. It is possible to project that some tree species will have decreased growth and others increased growth, but the magnitude of growth changes is uncertain. Finally, species distribution and abundance are likely to change in a warmer climate, but the magnitude, geographic specificity, and rate of future changes are uncertain.

Description of confidence and likelihood

Published literature and model projections imply *high confidence* that more frequent extreme weather events will increase the frequency and extent of large ecological disturbances, driving rapid (months to years) and often persistent changes in forest structure and function across large landscapes. Forests are long-lived and inherently resilient to climatic variability, so long-term monitoring (of, for example, growth and productivity, structure, regeneration, and species distribution and abundance) will be needed to confirm the direct effects of incremental changes in temperature. As a result, there is *medium confidence* that changes resulting from direct (but gradual) climate change and less severe disturbances will occur in the context of altered forest productivity, health, and species distribution and abundance that occur at longer timescales (decades to centuries).

Key Message 2

Ecosystem Services

It is very likely that climate change will decrease the ability of many forest ecosystems to provide important ecosystem services to society. Tree growth and carbon storage are expected to decrease in most locations as a result of higher temperatures, more frequent drought, and increased disturbances (*medium confidence*). The onset and magnitude of climate change effects on water resources in forest ecosystems will vary but are already occurring in some regions (*high confidence*).

Description of evidence base

Altered forest conditions caused by a changing climate are likely to influence the quantity and quality of many of the ecosystem services that humans derive from forests, and climate change is expected to increase the frequency and severity of natural disturbances in the coming decades and to reduce forest growth in most places.[18] Extreme high temperatures can also cause heat-related stress in vegetation and exacerbate drought conditions, potentially increasing tree mortality and reducing forest productivity.[7,166] Positive effects of carbon dioxide (CO_2) on growth will be negated in some species and locations by low soil fertility[167] and by air pollutants such as ground-level ozone, where concentrations of those pollutants are high enough to cause toxic effects in plants.[84]

Most evidence suggests that increased carbon sinks (caused by higher growth rates and more forest area in some regions) will not be sufficient to offset higher emissions from increased disturbances and enhanced release of carbon from decomposition in the future.[114,168,169,170] U.S. forests

are projected to continue to sequester carbon but at declining rates caused by land-use change and aging forests.[18] In the western United States, the aging of forests, coupled with disturbance dynamics, is projected to diminish carbon sequestration to negligible levels by around 2050, and some forests (for example, dry western forests with frequent fire and some eastern hardwood forests) will likely become a carbon source.[18] Younger productive forests in the eastern United States portend high carbon uptake rates, although harvest-related emissions substantially reduce the net effect on atmospheric carbon.

Land-use change that increases forest cover (such as cropland converted to forestland) is a major contributor to reductions in atmospheric CO_2,[116] but this conversion is expected to slow in the near future.[118] The estimated net carbon flux in the United States associated with forestland conversion is approximately zero, with gains in forestland constituting +23 teragrams (Tg) of carbon per year and losses resulting in emissions of –23 Tg carbon per year over the last decade. The estimated emissions constitute decades, and in some cases centuries, of accumulated carbon within forest ecosystems, which is abruptly or gradually released to the atmosphere during conversion from forest to nonforest land. In contrast, gains in forestland represent carbon sequestration only from new growth of live biomass and the accumulation of newly dead organic matter over the 20 or so years since the renewal of forest cover.

Economic conditions and population growth will affect national and global production and consumption of wood products, which can temporarily sequester carbon (currently 189 Tg carbon per year, or 8% of the global forest sink).[120] Increases in wood products carbon are contingent on a sustained or increasing rate of harvest removals of forest carbon or on a shift toward forest products that exist for long periods of time before they are no longer suitable for reuse or recycling. In the United States, 76% of the annual domestic harvest input to the wood products pool in 2015 (110 Tg carbon) was offset by release processes (84 Tg carbon), yielding a corresponding net increase in wood products of 26 Tg carbon.[14] However, if harvest rates decline (as they did in 2007–2009, during the last economic recession), net additions to wood products will likely be lower than emissions from wood harvested in prior years.[14] Looking ahead, carbon storage in wood products is expected to increase by 7–8 Tg carbon per year over the next 25 years.[171]

Snowfall amount, timing, and melt dynamics are affecting water availability and stream water quality in the western United States, where less precipitation is falling as snow and more as rain in winter months, leading to longer and drier summer seasons.[121] Furthermore, rapid opening of forests in the western United States by wildfire has caused faster spring snowmelt through increased solar radiation and decreased reflectivity of radiation from charcoal,[128] leading to drier summer conditions that offset increased water yield following a disturbance.[127] The persistence of winter snowpack in the northeastern United States has declined over the last few decades; mid-winter thaws have become more common, and snowmelt flushing of mobilized soil nutrients into streams has become less common, although increased variability in climate–hydrology interactions can alter flushing.[172]

Major uncertainties

It is difficult to identify geographically specific changes in forest conditions at fine scales because of high spatial variability in forest structure and function and variability in projections of climate change and how it will affect large disturbances (drought, wildfire, insect outbreaks). Uncertainties

about the rate and magnitude of climate change effects on carbon sequestration are moderately high, because it is difficult to project future trends in forest cover and socioeconomic influences on forest management (for example, demand for wood products, bioenergy). Although empirical evidence for young trees indicates that atmospheric enrichment of CO_2 can enhance tree growth, few long-term data on mature trees are available on which to base inferences about long-term forest productivity.[173] Temporal patterns and magnitude of carbon sequestration, especially after 2050, will be affected by uncertainties related to future land-use conversions (from forests to other uses and vice versa) and the production of wood products.

Description of confidence and likelihood

Because of variability in forest structure and function and species-level variation in adaptive capacity to climate change, it is difficult to project future changes in forest conditions at smaller than regional scales. Hence, there is *medium confidence* about how ecosystem services will be affected in different forest ecosystems, including effects on tree growth and carbon storage, as a function of higher temperature, more frequent drought, and increased disturbance. Observations from recent droughts and changing snowfall/snowmelt dynamics provide *high confidence* that climate change effects on water are already occurring in some regions, although the onset and magnitude of future effects will vary regionally.

Key Message 3

Adaptation

Forest management activities that increase the resilience of U.S. forests to climate change are being implemented (*high confidence*), with a broad range of adaptation options for different resources, including applications in planning (*medium confidence*). The future pace of adaptation will depend on how effectively social, organizational, and economic conditions support implementation (*high confidence*).

Description of evidence base

Climate change vulnerability assessments and adaptation planning efforts for forest ecosystems have been conducted at many locations (for example, forests in the western United States and upper Midwest) over the last decade.[19,140,141,144,174] These efforts have produced a broad range of adaptation options, including climate-informed practices for forest density management, water management, road management, and restoration.[19,144,175]

In general, practices that mitigate stressors in forest and aquatic systems increase resistance (the ability of a system to withstand a perturbation) and resilience (the ability of a system to return to a previous state after a perturbation) to climate change.[127,144] For example, restoring riparian vegetation helps to stabilize stream banks and provides shade to streams, thus helping to moderate stream temperatures.[127] Similarly, culvert replacement under forest roads can improve fish passage and reduce damage from flooding events.[127] Tools are now available to help in the prioritization of aquatic and riparian habitat restoration.[150]

There is strong evidence that stand density management can increase forest resistance and resilience to disturbances, including wildfire and bark beetle infestations in dry forest types. A

growing body of evidence suggests that reducing stand density in most forest types can increase forest resilience to drought by increasing soil water availability and decreasing competition.[146,148,176] Reductions in stand density, combined with hazardous fuel treatments, can increase resilience to wildfire by reducing wildfire intensity and crown fires in western dry conifer forests and southern conifer forests.[141,145,174] Evidence also suggests that stand density management can reduce the incidence of bark beetles and subsequent mortality in some coniferous forests (for example, lodgepole pine forests).[177] All of these practices—in addition to "firewise" practices near buildings and infrastructure on public and private lands [178] and the use of prescribed fire where possible—improve the resilience of organizations and communities to increased frequency of wildfire.[179]

Wildfire has been an important disturbance in aquatic ecosystems for millennia,[180] and its frequency will increase in the future. Management responses to changing climate and fire regimes will need to be developed in the context of how past land use impaired aquatic function. Coordinating restoration in adjacent riparian and forest habitats can help ensure that beneficial effects of fire are retained across the aquatic–terrestrial interface.[181]

Examples of on-the-ground implementation of adaptation options to increase ecosystem resistance and resilience to climate change are emerging in the scientific literature.[138,139,141] However, exploration of potential management actions is more common than on-the-ground action,[18,19,127,140,145,175] suggesting that implementation is still in the early stages.

Major uncertainties

Evidence for the long-term effectiveness of climate change adaptation is derived primarily from our current understanding of how specific actions (for example, forest thinning, restoration of riparian systems, conservation of biodiversity) sustain the functionality of terrestrial and aquatic systems.[127] Physical and biological conditions of ecosystems are constantly changing, and interactions among multiple ecosystem stressors could have unforeseen outcomes on ecosystem composition, structure, and function. Thus, the long-term effectiveness of adaptation actions for increasing forest resistance and resilience to climate change is uncertain until a sufficient time series of monitoring data is available, requiring decades of observations.

The future pace of adaptation and barriers to its implementation are also uncertain, and it is expected that many forest management challenges will persist in the future. However, new challenges and barriers may emerge,[182] and it is difficult to predict how society and organizations will respond.

Description of confidence and likelihood

There is *high confidence* that climate change adaptation planning in forest management is occurring, particularly in U.S. federal agencies (especially national forests in the western and northeastern United States) (Ch. 28: Adaptation)[19,140,175] and Native American tribes.[142] Because of the limited number of examples in the scientific literature, there is *medium confidence* that adaptation planning is progressing to the application stage, where forest management plans are altered and on-the-ground management activities are implemented to mitigate the effects of climate change. However, there is *high confidence* that future progress in climate change adaptation planning and implementation will depend on social, organizational, and economic conditions.

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7 Ecosystems, Ecosystem Services, and Biodiversity

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On the Web: https://nca2018.globalchange.gov/chapter/ecosystems

7 Ecosystems, Ecosystem Services, and Biodiversity

Kodiak National Wildlife Refuge, Alaska

Key Message 1

Impacts on Species and Populations

Climate change continues to impact species and populations in significant and observable ways. Terrestrial, freshwater, and marine organisms are responding to climate change by altering individual characteristics, the timing of biological events, and their geographic ranges. Local and global extinctions may occur when climate change outpaces the capacity of species to adapt.

Key Message 2

Impacts on Ecosystems

Climate change is altering ecosystem productivity, exacerbating the spread of invasive species, and changing how species interact with each other and with their environment. These changes are reconfiguring ecosystems in unprecedented ways.

Key Message 3

Ecosystem Services at Risk

The resources and services that people depend on for their livelihoods, sustenance, protection, and well-being are jeopardized by the impacts of climate change on ecosystems. Fundamental changes in agricultural and fisheries production, the supply of clean water, protection from extreme events, and culturally valuable resources are occurring.

Key Message 4

Challenges for Natural Resource Management

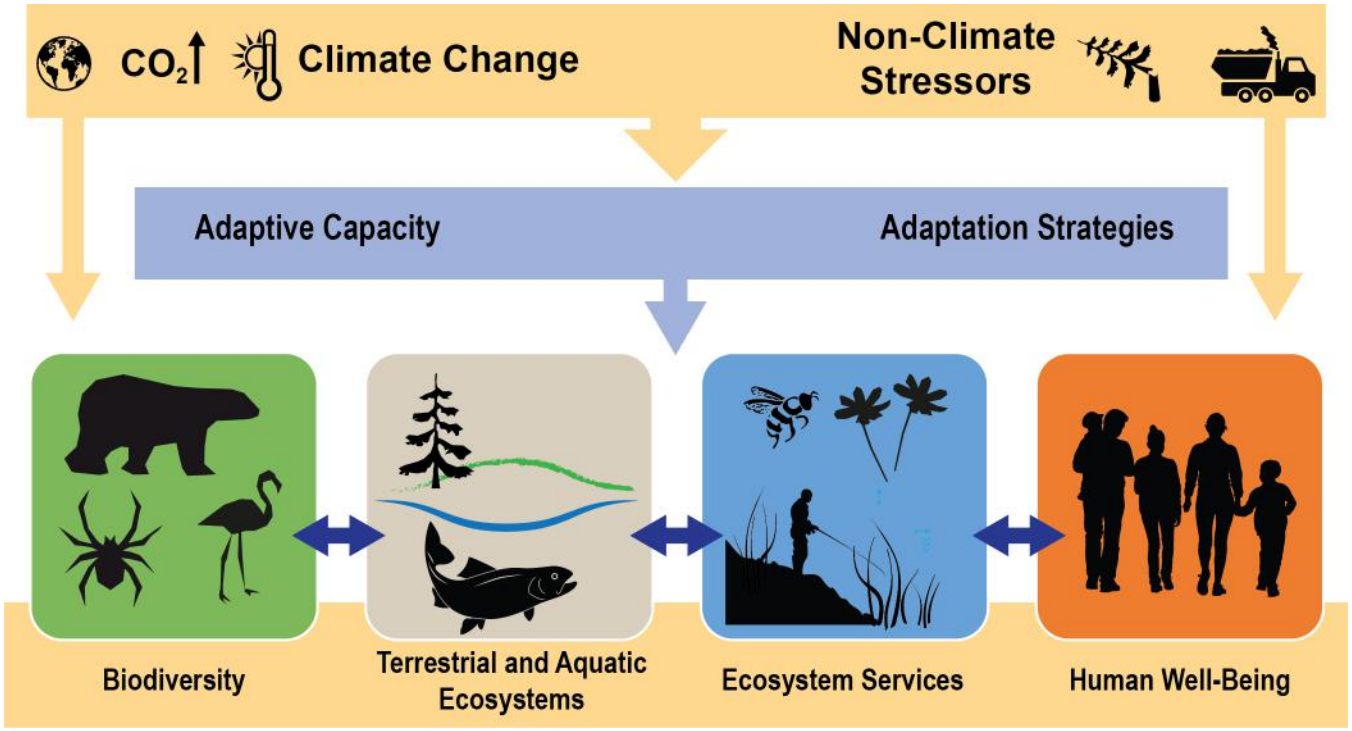
Traditional natural resource management strategies are increasingly challenged by the impacts of climate change. Adaptation strategies that are flexible, consider interacting impacts of climate and other stressors, and are coordinated across landscape scales are progressing from theory to application. Significant challenges remain to comprehensively incorporate climate adaptation planning into mainstream natural resource management, as well as to evaluate the effectiveness of implemented actions.

Executive Summary

Biodiversity—the variety of life on Earth—provides vital services that support and improve human health and well-being. Ecosystems, which are composed of living things that interact with the physical environment, provide numerous essential benefits to people. These benefits, termed ecosystem services, encompass four primary functions: provisioning materials, such as food and fiber; regulating critical parts of the environment, such as water quality and erosion control; providing cultural services, such as recreational opportunities and aesthetic value; and providing supporting services, such as nutrient cycling.[1] Climate change poses many threats and potential disruptions to ecosystems and biodiversity, as well as to the ecosystem services on which people depend.

Building on the findings of the Third National Climate Assessment (NCA3),[2] this chapter provides additional evidence that climate change is significantly impacting ecosystems and biodiversity in the United States. Mounting evidence also demonstrates that climate change is increasingly compromising the ecosystem services that sustain human communities, economies, and well-being. Both human and natural systems respond to change, but their ability to respond and thrive under new conditions is determined by their adaptive capacity, which may be inadequate to keep pace with rapid change. Our understanding of climate change impacts and the responses of biodiversity and ecosystems has improved since NCA3. The expected consequences of climate change will vary by region, species, and ecosystem type. Management responses are evolving as new tools and approaches are developed and implemented; however, they may not be able to overcome the negative impacts of climate change. Although efforts have been made since NCA3 to incorporate climate adaptation strategies into natural resource management, significant work remains to comprehensively implement climate-informed planning. This chapter presents additional evidence for climate change impacts to biodiversity, ecosystems, and ecosystem services, reflecting increased confidence in the findings reported in NCA3. The chapter also illustrates the complex and interrelated nature of climate change impacts to biodiversity, ecosystems, and the services they provide.

Climate Change, Ecosystems, and Ecosystem Services



Climate and non-climate stressors interact synergistically on biological diversity, ecosystems, and the services they provide for human well-being. The impact of these stressors can be reduced through the ability of organisms to adapt to changes in their environment, as well as through adaptive management of the resources upon which humans depend. Biodiversity, ecosystems, ecosystem services, and human well-being are interconnected: biodiversity underpins ecosystems, which in turn provide ecosystem services; these services contribute to human well-being. Ecosystem structure and function can also influence the biodiversity in a given area. The use of ecosystem services by humans, and therefore the well-being humans derive from these services, can have feedback effects on ecosystem services, ecosystems, and biodiversity. *From Figure 7.1 (Sources: NOAA, USGS, and DOI).*

State of the Sector

All life on Earth, including humans, depends on the services that ecosystems provide, including food and materials, protection from extreme events, improved quality of water and air, and a wide range of cultural and aesthetic values. Such services are lost or compromised when the ecosystems that provide them cease to function effectively. Healthy ecosystems have two primary components: the species that live within them, and the interactions among species and between species and their environment. Biodiversity and ecosystem services are intrinsically linked: biodiversity contributes to the processes that underpin ecosystem services; biodiversity can serve as an ecosystem service in and of itself (for example, genetic resources for drug development); and biodiversity constitutes an ecosystem good that is directly valued by humans (for example, appreciation for variety in its own right).[3] Significant environmental change, such as climate change, poses risks to species, ecosystems, and the services that humans rely on. Consequently, identifying measures to minimize, cope with, or respond to the negative impacts of climate change is necessary to reduce biodiversity loss and to sustain ecosystem services.[4]

This chapter focuses on the impacts of climate change at multiple scales: the populations and species of living things that form ecosystems; the properties and processes that support ecosystems; and the ecosystem services that underpin human communities, economies, and well-being. The key messages from NCA3 (Table 7.1) have been strengthened over the last four years by new research and monitoring networks. This chapter builds on the NCA3 findings and specifically emphasizes how climate impacts interact with non-climate stressors to affect ecosystem services. Furthermore, it describes new advances in climate adaptation efforts, as well as the challenges natural resource managers face when seeking to sustain ecosystems or to mitigate climate change (Figure 7.1).

Key Messages from Third National Climate Assessment

Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.
Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.
Landscapes and seascapes are changing rapidly, and species, including many iconic species, may disappear from regions where they have been prevalent or become extinct, altering some regions so much that their mix of plant and animal life will become almost unrecognizable.
Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.
Whole system management is often more effective than focusing on one species at a time, and can help reduce the harm to wildlife, natural assets, and human well-being that climate disruption might cause.

Table 7.1: Key Messages from the Third National Climate Assessment Ecosystems, Biodiversity, and Ecosystem Services Chapter[2]

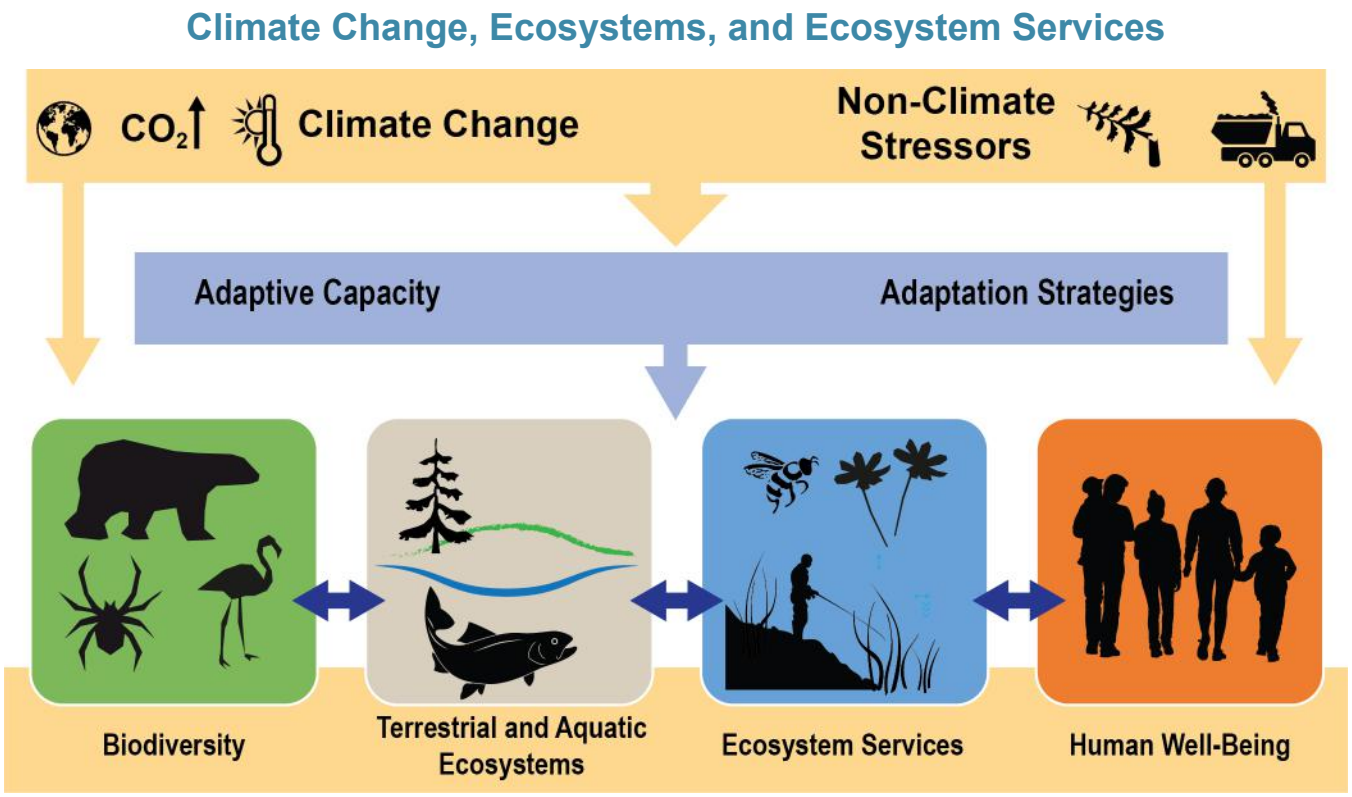


Figure 7.1: Climate and non-climate stressors interact synergistically on biological diversity, ecosystems, and the services they provide for human well-being. The impact of these stressors can be reduced through the ability of organisms to adapt to changes in their environment, as well as through adaptive management of the resources upon which humans depend. Biodiversity, ecosystems, ecosystem services, and human well-being are interconnected: biodiversity underpins ecosystems, which in turn provide ecosystem services; these services contribute to human well-being. Ecosystem structure and function can also influence the biodiversity in a given area. The use of ecosystem services by humans, and therefore the well-being humans derive from these services, can have feedback effects on ecosystem services, ecosystems, and biodiversity. Sources: NOAA; USGS; DOI.

Species and Populations

There is increasing evidence that climate change is impacting biodiversity, and species and populations are responding in a variety of ways. Individuals may acclimate to new conditions by altering behavioral, physical, or physiological characteristics, or populations may evolve new or altered characteristics that are better suited to their current environment. Additionally, populations may track environmental conditions by moving to new locations. The impacts of climate change on biodiversity have been observed across a range of scales, including at the level of individuals (such as changes in genetics, behavior, physical characteristics, and physiology), populations (such as changes in the timing of life cycle events), and species (such as changes in geographic range).[5]

Changes in individual characteristics: At an individual level, organisms can adapt to climate change through shifts in behavior, physiology, or physical characteristics.[5,6,7,8] These changes have been observed across a range of species in terrestrial, freshwater, and marine systems.[5,6,7,8] Some individuals have the ability to immediately alter characteristics in response to new environmental conditions. Behavioral changes, such as changes in foraging, habitat use, or predator avoidance, can provide an early indication of climate change impacts because they are often observable before other impacts are apparent.[6]

However, some immediate responses to environmental conditions are not transmitted to the next generation. Ultimately, at least some evolutionary

response is generally required to accommodate long-term, directional change.[9] Although relatively fast evolutionary changes have been documented in the wild,[10,11,12] rapid environmental changes can exceed the ability of species to track them.[13] Thus, evidence to date suggests that evolution will not fully counteract negative effects of climate change for most species. Importantly, many human-caused stressors, such as habitat loss or fragmentation (Figure 7.2) (see also Ch. 5: Land Changes, "State of the Sector" and KM 2), reduce the abundance as well as the genetic diversity of populations. This in turn compromises the ability of species and populations to cope with additional disturbances.[14]

Changes in phenology: The timing of important biological events is known as phenology and is a key indicator of the effects of climate change on ecological communities.[16,17,18,19] Many plants and animals use the seasonal cycle of environmental events (such as seasonal temperature transitions, melting ice, and seasonal precipitation patterns) as cues for blooming, reproduction, migration, or hibernation. Across much of the United States, spring is starting earlier in the year relative to 20th-century averages, although in some regions spring onset has been delayed (Figure 7.3) (see also Ch. 1: Overview, Figure 1.2j).[20,21,22] In marine and freshwater systems, the transition from winter to spring temperatures[23] and the melting of ice[24] are occurring earlier in the spring, with significant impacts on the broader ecosystem. Phytoplankton can respond rapidly to such changes, resulting in significant shifts in the timing of phytoplankton blooms and causing cascading food web effects (Ch. 9: Oceans, KM 2).[19,24]

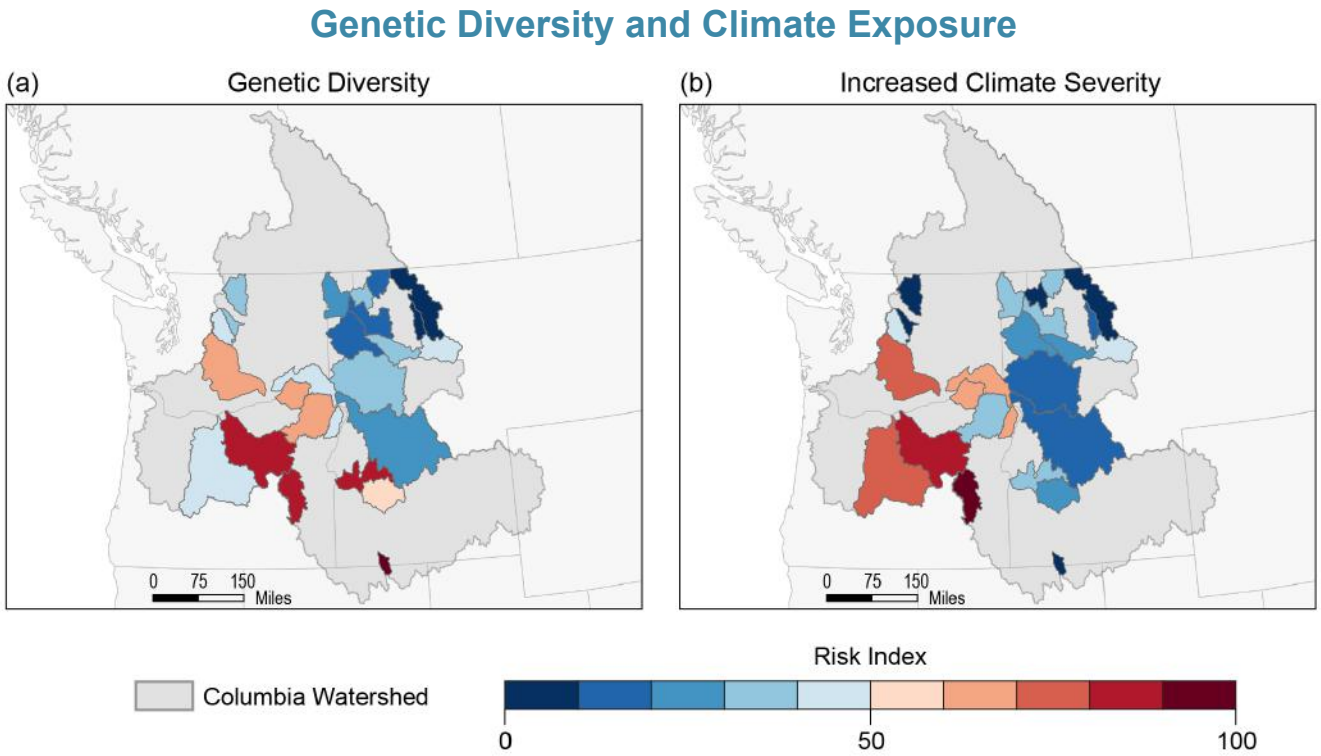


Figure 7.2: Genetic diversity is the fundamental basis of adaptive capacity. Throughout the Pacific Northwest, (a) bull trout genetic diversity is lowest in the same areas where (b) climate exposure is highest; in this case, climate exposure is a combination of maximum temperature and winter flood risk. Sub-regions within the broader Columbia River Basin (shaded gray) represent different watersheds used in the vulnerability analysis. Values are ranked by threat, such that the low genetic diversity and high climate exposure are both considered "high" threats (indicated as red in the color gradient). Source: adapted from Kovach et al. 2015.[15]

Trends in First Leaf and First Bloom Dates

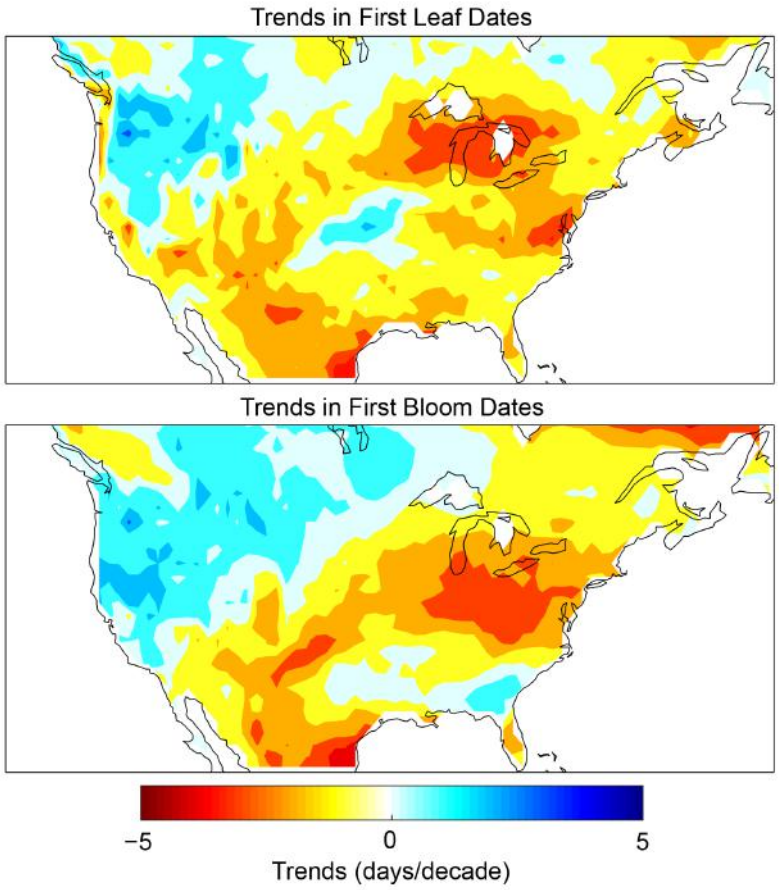


Figure 7.3: These maps show observed changes in timing of the start of spring over the period 1981–2010, as represented by (top) an index of first leaf date (the average date when leaves first appear on three indicator plants) and (bottom) an index of first bloom date (the average date when blossoms first appear on three indicator plants). Reds and yellows indicate negative values (a trend toward earlier dates of first leaf or bloom); blues denote positive values (a trend toward later dates). Units are days per decade. Indices are derived from models driven by daily minimum and maximum temperature throughout the early portion of the growing season. Source: adapted from Ault et al. 2015.[21]

One emerging trend is that the rate of phenological change varies across trophic levels (position in a food chain, such as producers and consumers),[25,26] resulting in resource mismatches and changes to species interactions. Migratory species are particularly vulnerable to phenological mismatch if their primary food source is not available when they arrive at their feeding grounds or if they lack the flexibility to shift to other food sources.[27,28,29]

Changes in range: Climate change is resulting in large-scale shifts in the range and abundance of species, which are altering terrestrial, freshwater, and marine ecosystems.[2,30,31,32,33] Range shifts reflect changes in the distribution of a population in response to changing environmental conditions and can occur as a result of directional movement or different rates of survival (Ch. 1: Overview, Figure 1.2h). The ability of a species to disperse affects the rate at which species can shift their geographic range in response to climate change and hence is an indicator of adaptive capacity.[34] Climate change has led to range contractions in nearly half of studied terrestrial animals and plants in North America; this has generally involved shifts northward or upward in elevation.[35] High-elevation species may be more exposed to climate change than previously expected[36] and seem particularly affected by range shifts.[37] In marine environments, many larval and adult

fish have also shown distribution shifts—primarily northward, but also along coastal shelves and to deeper water—that correspond with changing conditions.[38]

Species vary in the extent to which they track different aspects of climate change (such as temperature and precipitation),[39,40,41] which has the potential to cause restructuring of communities across many ecosystems. This variation is increasingly being considered in research efforts in order to improve predictions of species range shifts.[42,43,44] Finally, habitat fragmentation and loss of connectivity (due to urbanization, roads, dams, etc.) can prevent species from tracking shifts in their required climate; efforts to retain, restore, or establish climate corridors can, therefore, facilitate movements and range shifts.[18,45,46,47]

Ecosystems

Climate-driven changes in ecosystems derive from the interacting effects of species- and population-level responses, as well as the direct impacts of environmental drivers. Since NCA3, there have been advances in our understanding of several fundamental ecosystem properties and characteristics, including: primary production, which defines the overall capacity of an ecosystem to support life; invasive species; and emergent properties and species interactions. Particular ecosystems that are experiencing specific climate change impacts, such as ocean acidification (Ch. 9: Oceans), sea level rise (Ch. 8: Coastal, KM 2), and wildfire (Ch. 6: Forests, KM 1), can be explored in more detail in sectoral and regional chapters (see also Ch. 1: Overview, Figures 1.2i, 1.2g, and 1.2k).

Changing primary productivity: Almost all life on Earth relies on photosynthetic organisms. These primary producers, such as plants and phytoplankton, are responsible for producing Earth's oxygen, are the base of most food webs, and are important components of carbon cycling and sequestration. Diverse observations suggest that global terrestrial primary production has increased over the latter 20th and early 21st centuries.[48,49,50,51] This change has been attributed to a combination of the fertilizing effect of increasing atmospheric CO_2, nutrient additions from human activities, longer growing seasons, and forest regrowth, although the precise contribution of each factor remains unresolved (Ch. 6: Forests, KM 2; Ch. 5: Land Changes, KM 1).[50,51,52] Regional trends, however, may differ significantly from global averages. For example, heat waves, drought, insect outbreaks, and forest fires in some U.S. regions have killed millions of trees in recent years (Ch. 6: Forests, KM 1 and 2).

Marine primary production depends on a combination of light, which is prevalent at the ocean's surface, and nutrients, which are available at greater depths. The separation between surface and deeper ocean layers has grown more pronounced over the past century as surface waters have warmed.[53] This has likely increased nutrient limitation in low- and midlatitude oceans. Direct evidence for declines in primary productivity, however, remains mixed.[54,55,56,57,58,59,60]

Invasive species: Climate change is aiding the spread of invasive species (nonnative organisms whose introduction to a particular ecosystem causes or is likely to cause economic or environmental harm). Invasive species have been recognized as a major driver of biodiversity loss.[61,62,63] The worldwide movement of goods and services over the last 200 years has resulted in an increasing rate of introduction of nonnative species globally,[64,65] with no sign of slowing.[66] Global ecological and economic costs associated with damages caused by nonnative species and their control are substantial (more than $1.4 trillion annually).[61] The introduction of invasive species, along with climate-driven range shifts, is creating new species interactions and novel ecological communities, or combinations of species with

no historical analog.[67,68] Climate change can favor nonnative invading species over native ones.[69,70] Extreme weather events aid species invasions by decreasing native communities' resistance to their establishment and by occasionally putting native species at a competitive disadvantage, although these relationships are complex and warrant further study.[71,72,73,74] Climate change can also facilitate species invasions through physiological impacts, such as by increasing per capita reproduction and growth rates.[69,75,76]

Changing species interactions and emergent properties: Emergent properties of ecosystems refer to changes in the characteristics, function, or composition of natural communities. This includes changes in the strength and intensity of interactions among species, altered combinations of community members (known as assemblages), novel species interactions, and hybrid or novel ecosystems.[78] There is mounting evidence that in some systems (such as plant–insect food webs), higher trophic levels are more sensitive than lower trophic levels to climate-induced changes in temperature, water availability,[79,80,81] and extreme events.[82] Predator responses to these stressors can lead to higher energetic needs and increased consumption,[83] shifts or expansion in seasonal demand on prey resources, or resource mismatches.[84,85] Some predators may be able to adapt to changing conditions by switching to alternative or novel food sources[86] or adjusting their behavior to forage in cooler habitats to alleviate heat stress.[87] Such changes at higher trophic levels directly affect the energetic demands and mortality rates of prey[88] and have important impacts on ecosystem functioning, such as biological activity and productivity (as indicated by community respiration rates),[89] and on the flow of energy and nutrients within communities and across habitats. For example, in Alaska, brown bears have recently altered their preference for salmon to earlier-ripening berries, changing both salmon mortality rates and the transfer of oceanic nutrients to terrestrial habitats.[90] Warming is changing community composition, as species with lower tolerances to disturbance[91] and nonoptimal conditions[92] are outcompeted. Declining diversity in life histories as a result of climate change is also expected to result in more uniform, less varied population structures, in turn resulting in increased competition and potentially contributing to local extinctions and reduced community resilience.[29,93]

Lionfish are an invasive species in the Atlantic, and their range is projected to expand closer to the U.S. Atlantic coastline in the future as a result of climate change. Photo credit: G.P. Schmahl, NOAA Flower Garden Banks National Marine Sanctuary.

Projected Range Expansion of Invasive Lionfish

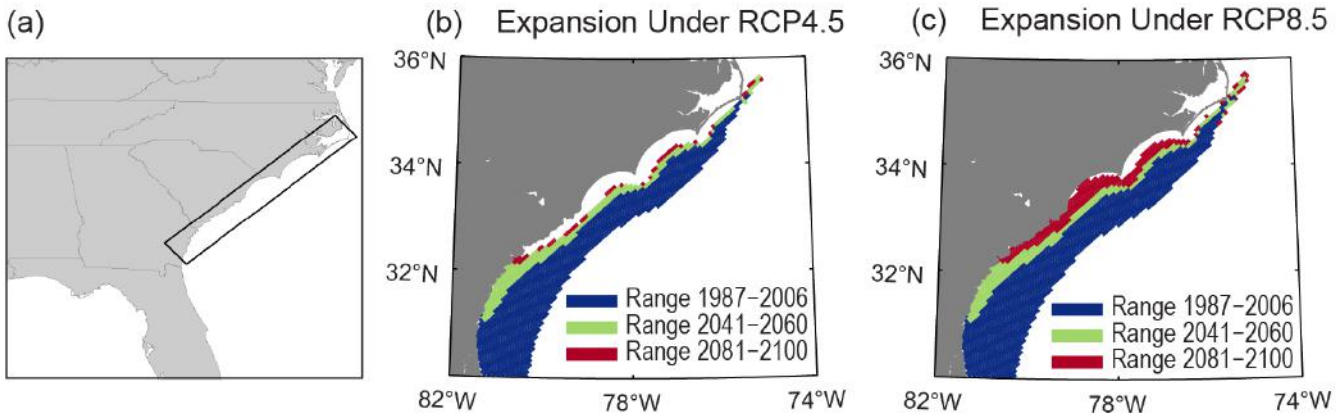


Figure 7.4: Lionfish, native to the Pacific Ocean, are an invasive species in the Atlantic. Their range is projected to expand closer to (a) the U.S. Atlantic coastline as a result of climate change. The maps show projected range expansion of the invasive lionfish in the southeast United States by mid-century (green) and end of the century (red), based on (b) the lower and (c) higher scenarios (RCP4.5 and RCP8.5, respectively), as compared to their recently observed range (blue). The projected range shifts under a higher scenario (RCP8.5) represents a 45% increase over the current year-round range. Venomous lionfish are opportunistic, generalist predators that consume a wide variety of invertebrates and fishes and may compete with native predatory fishes. Expansion of their range has the potential to increase the number of stings of divers and fishers. Source: adapted from Grieve et al. 2016.[77]

Ecosystem Services

Increasing evidence since NCA3 demonstrates that climate change continues to affect the availability and delivery of ecosystem services, including changes to provisioning, regulating, cultural, and supporting services. Humans, biodiversity, and ecosystem processes interact with each other dynamically at different temporal and spatial scales.[94] Thus, the climate-related changes to ecosystems and biodiversity discussed in this and other chapters of this report all have consequences for numerous ecosystem services. In addition, these climate-related impacts interact with other non-climate stressors, such as pollution, overharvesting, and habitat loss, to produce compounding impacts on ecosystem services.[95,96]

The adaptive capacity of human communities to deal with these changes will partly determine the magnitude of the resulting impacts to ecosystem services. For example, the shifting range of fish stocks (Ch. 9: Oceans, KM 2), an example of a provisioning ecosystem service, may require vessels to travel further from port, invest in new fishing equipment, or stop fishing altogether; each of these responses implies increasing levels of costs to society.[97] A reduction in biodiversity that impacts the abundance of charismatic and aesthetically valuable organisms, such as coral reefs, can lead to a reduction in wildlife-related ecotourism and may result in negative economic consequences for the human communities that rely on them for income.[3] Climate change can also impact ecosystem services such as the regulation of climate and air, water, and soil quality.[98] Although climate change impacts on ecosystem services will not be uniformly negative, even apparently positive impacts of climate change can result in costly changes. For example, in areas experiencing longer growing seasons (Ch. 10: Ag & Rural, KM 3), farmers would need to shift practices and invest in new infrastructure (Ch. 12: Transportation, KM 1 and 2) in order to fully realize the benefits of these climate-driven changes. Moreover, different human communities and segments of society will be more vulnerable than others based on their ability to adapt; jurisdictional borders, for instance, may limit human migration in response to climate change.[99]

Oyster reefs exemplify the myriad ways in which ecosystem components support ecosystem services, including water quality regulation, nutrient and carbon sequestration, habitat formation, and shoreline protection. These services are reduced when oyster reefs are impacted by climate change through, for example, sea level rise[100,101] and ocean acidification.[102] A recent study estimated that the economic value of the non-harvest ecosystem services provided by oyster reefs ranges from around $5,500 to $99,400 (in 2011 dollars) per year per hectare. The value of shoreline protection varied depending on the location but had the highest possible value of up to $86,000 per hectare per year (in 2011 dollars).[103] Coral reefs, which provide shoreline protection and support fisheries and recreation, are also threatened by ocean warming and acidification. The loss of recreational benefits associated with coral reefs in the United States is projected to be $140 billion by 2100 (in 2015 dollars) under a higher scenario (RCP8.5) (Ch. 9: Oceans, KM 1).[104]

Regional Summary

All regions and ecosystems of the United States are experiencing the impacts of climate change. However, impacts will vary by region and ecosystem: not all areas will experience the same types of impacts, nor will they experience them to the same degree (Ch. 2: Climate, KM 5 and 6). Regional variation in climate impacts are covered in detail in other sectoral and regional chapters of the Fourth National Climate Assessment. However, in Figure 7.5, a wide range of regional examples are provided at multiple scales to demonstrate the varied ways in which biodiversity, ecosystems, and ecosystem services are being impacted around the United States.

Regional Ecosystems Impacts

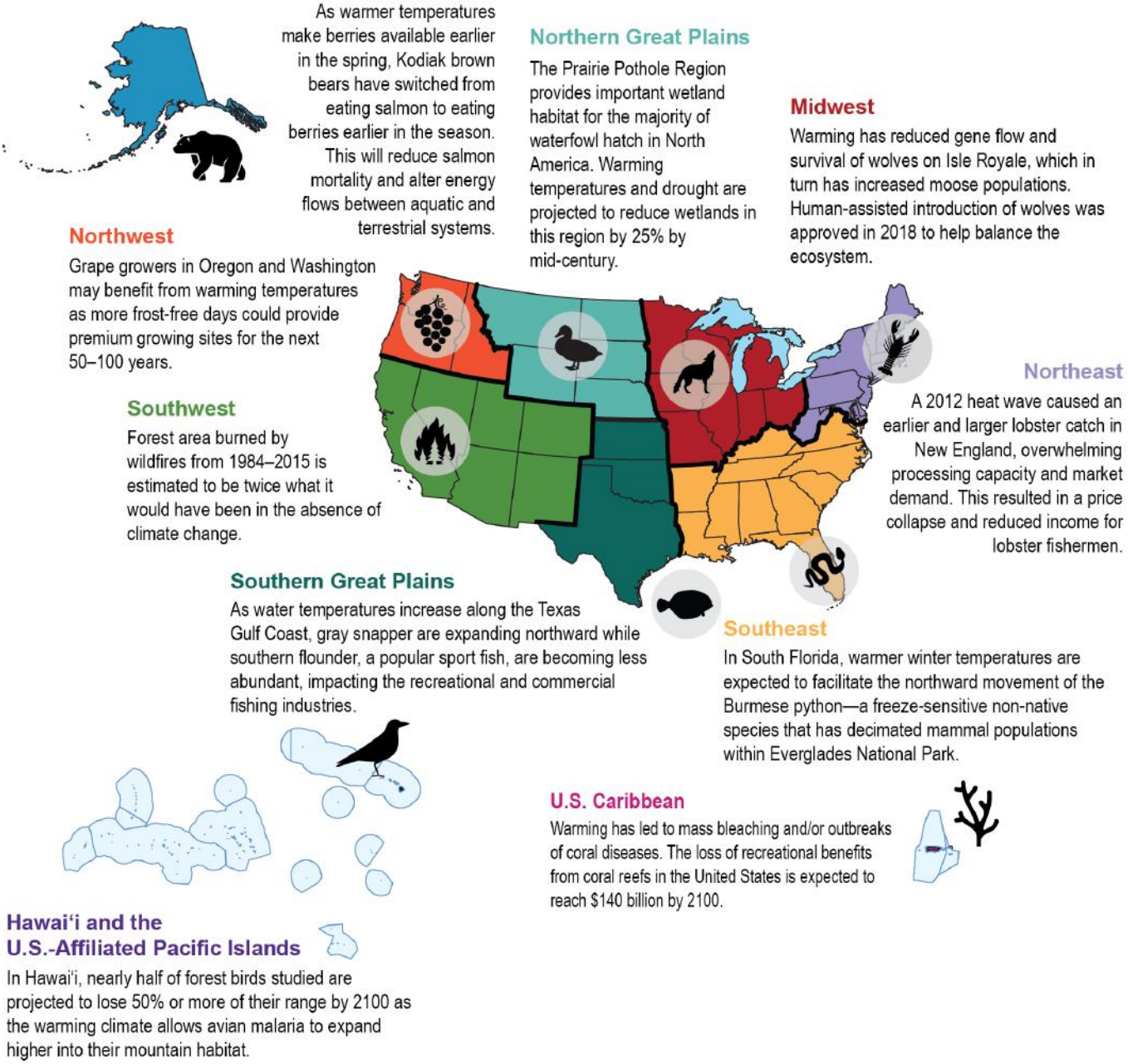


Figure 7.5: This figure shows selected examples of impacts to biodiversity, ecosystems, and ecosystem services that are linked to climate change throughout the United States. See the online version at https://nca2018.globalchange.gov/chapter/7#fig-7-5 for more examples and references. Source: adapted from Groffman et al. 2014.

Key Message 1

Impacts on Species and Populations

Climate change continues to impact species and populations in significant and observable ways. Terrestrial, freshwater, and marine organisms are responding to climate change by altering individual characteristics, the timing of biological events, and their geographic ranges. Local and global extinctions may occur when climate change outpaces the capacity of species to adapt.

Climate change continues to alter species' characteristics, phenologies, abundances, and geographical ranges, but not all species are affected equally. Generalists (species that use a wide range of resources) are better able to adapt to or withstand climate-driven changes,[90] while specialists (species that depend on just a few resources), small or isolated populations, and species at the edge of their ranges have limited abilities to adjust to unfavorable or new environmental conditions.[27,105,106]

Species' survival depends on the presence and flexibility of traits to adapt to climate change; traits may occur within the existing genetic structure of a population (that is, plasticity) or arise through evolution. Changes in individual characteristics are one of the most immediate mechanisms an organism has to cope with environmental change, and species have demonstrated both plastic and evolutionary responses to recent climate change.[9,10,11,12] For example, snowshoe hares rely on coat color to camouflage them from predators, but earlier spring snowmelts have increased the number of white animals on snowless backgrounds. While individual animals have exhibited some ability to adjust the rate of molting, they have limited capacity to adjust the timing of color change.[9] Consequently, evolution in the timing of molting may be needed to ensure persistence under future climate conditions.

Shifts in range and phenology also indicate species' ability to cope with climate change through the presence and flexibility of particular traits (for example, behavior and dispersal abilities). In studies spanning observational periods of up to 140 years, terrestrial animal communities have shifted ranges an average of 3.8 miles per decade.[107] Larger shifts of up to 17.4 miles per decade have been recorded for marine communities[17,38,108] in observations spanning up to a century. Birds in North America have shifted their ranges in the last 60 years, primarily northward.[109] Pollinators have been affected, too, with decreases in abundance and shifts upslope seen over the past 35 years.[110] Models suggest that shifts in species' ranges will continue, with freshwater and marine organisms generally moving northward to higher latitudes and to greater depths and terrestrial species moving northward and to higher elevations.[111,112] However, this capacity to adapt to climate change through range shifts is not infinite: many organisms have limited dispersal ability and newly suitable habitat in which to colonize, and all organisms are limited in the range of environments to which they can adapt.

White snowshoe hares stand out in stark contrast against snowless backgrounds, leaving them more vulnerable to predators than their brown counterparts. Photo credit: L. S. Mills research photo by Jaco and Lindsey Barnard, University of Montana Mills Research Lab.

Shifts in phenology have been well documented in terrestrial, marine, and freshwater systems.[113] As with range shifts, changes to phenology are expected to continue as the climate warms.[114] Changes in phenology can have significant impacts on ecosystems and the services they provide, as evidenced by shifts in the production and phenology of commercially important marine groundfish,[38,115] inland fish species,[116] migratory fish such as salmon,[10,117,118] and invertebrates such as northern shrimp and lobster (Ch. 18: Northeast, KM 2 and Box 18.1).[119,120]

The many components of climate change (for example, rising temperatures, altered precipitation, ocean acidification, and sea level rise) can have interacting and potentially opposing effects on species and populations, which further complicates their responses to climate change.[41,121,122] In addition, species are responding to many other factors in addition to climate change, such as altered species interactions and non-climate stressors such as land-use change (Ch. 5: Land Changes, "State of the Sector" and KM 2) and resource extraction (for example, logging and commercial fishing).

Compounding stressors can result in species lagging behind temperature change and occupying nonoptimal conditions.[123] For example, iconic species of salmon have lost access to much of their historical habitat due to barriers or degradation caused by pollution and land-use change, leading to significant losses in spawning and cold water habitats that could have supported adaptation and provided refuge against increasing climate impacts.[124,125]

The rate and magnitude of climate impacts can exceed the abilities of even the most adaptable species and potentially lead to tipping points, which result in abrupt system changes and local extinctions.[126,127] For example, climate change appears to have contributed to the local extinction of populations of the Federally Endangered Karner blue butterfly in Indiana (Ch. 21: Midwest, KM 3). Compounded climate stress arises when populations with limited capacity to adapt also experience high exposure to climate change, posing substantial risks to certain ecosystems and the services they provide to society. Bull trout in the Northwest, for example, show the least genetic diversity in the same regions where summer temperature and winter streamflows are projected to be the highest due to climate change (Figure 7.2).[15] Further decline of salmon and trout will impact a cherished cultural resource, as well as popular sport and commercial fisheries. Identifying the most vulnerable species and understanding what makes them relatively more at risk than other species are, therefore, important considerations for prioritizing and implementing effective management actions.[35,127,128,129]

Key Message 2

Impacts on Ecosystems

Climate change is altering ecosystem productivity, exacerbating the spread of invasive species, and changing how species interact with each other and with their environment. These changes are reconfiguring ecosystems in unprecedented ways.

Climate change impacts also occur at the ecosystem scale, changing fundamental ecosystem characteristics, properties, and related ecosystem services; altering important trophic relationships; and affecting how species and populations interact with each other.

Because primary producers are the base of the food web, climate impacts to primary production can have significant effects that radiate throughout the entire ecosystem. While climate models project continued increases

in global terrestrial primary production over the next century,[130,131] these projections are uncertain due to a limited understanding of the impacts of continued CO_2 increases on terrestrial ecosystem dynamics;[132,133,134] the potential effects of nutrient limitation;[135] the impacts of fire[136] and insect outbreaks;[137] and an incomplete understanding of the impacts of changing climate extremes.[138,139] Furthermore, even without these factors, projections suggest decreasing primary production in many arid regions due to worsening droughts, similar to responses observed in the Southwest United States in recent years.[140,141,142] Modest to moderate declines in ocean primary production are projected for most low- to midlatitude oceans over the next century,[143,144,145] but regional patterns of change are less certain.[60,143,145] Most models project increasing primary productivity in the Arctic due to decreasing ice cover. This trend is supported by satellite-based observations of the primary productivity–ice cover relationship over the last 10–15 years.[146,147,148] Projections also suggest that changes in productivity will not be equal across trophic levels: changes in primary productivity are likely to be amplified at higher levels of the food web.[149,150,151] For example, small changes in marine primary productivity are likely to result in even larger changes to the biomass of fisheries catch.[152]

Varying phenological responses to climate change can also impact the food web and result in altered species interactions and resource mismatch.[17,153] Such mismatches can decrease the fitness of individuals, disrupt the persistence and resilience of populations, alter ecosystems and ecosystem services, and increase the risk of localized extinctions.[16,26,113,154,155] In marine ecosystems, rapid phenological changes at the base of the food web can create a mismatch with consumers,[156] disrupting the availability of food for young fish and changing the food web structure.[24,156]

In both terrestrial and aquatic environments, migratory species face the potential for resource mismatch. For example, a majority of migratory songbirds in North America have advanced their phenology in response to climate change, but for several species, such as the yellow-billed cuckoo and the blue-winged warbler, these changes have been outpaced by advancing vegetation in their breeding grounds and stopover sites.[28] The resulting mismatch between consumers and their food or habitat resources can result in population declines.[155]

In addition to changes in productivity and phenology, novel species interactions as a result of climate change can cause dramatic and surprising changes. For example, range expansions of tropical herbivorous fishes have changed previously kelp-dominated systems into kelp-free sites.[157] These novel combinations of species are expected to outcompete and potentially eliminate some native species, posing a significant threat to the long-term stability of iconic ecosystems and the services they provide.[157] A recent survey of 136 freshwater, marine, and terrestrial studies suggests that species interactions are often the immediate cause of local extinctions related to climate change.[158]

Climate change impacts to ecosystem properties are difficult to assess and predict because they arise from multiple and complex interactions across different levels of food webs, habitats, and spatial scales. Modeling and experimental studies are some of the few ways to assess complicated ecological interactions, especially in marine systems where direct observations of plants, fish, and animals are difficult.[67,159,160,161] There is strong consensus that trophic mismatches and asynchronies will occur, yet these are mostly predicted consequences, and few examples have been documented.[13,84,162,163] While theory and management principles for novel ecosystems are

new, strongly debated, and largely descriptive, they are also crucial for understanding and anticipating widespread ecosystem changes in the future.[164,165,166] For example, it remains largely uncertain which members of historical ecological communities and ecosystems will adapt in place or move into new locations to follow optimal ecological and environmental conditions.[167] Such uncertainties complicate management decisions regarding where and when human intervention is advisable to assist persistence.

It is also unclear how the restructuring of ecosystems will manifest in terms of the functioning and delivery of ecosystem services.[167,168] For example, along the Northeast Atlantic coast, native fiddler and blue crabs have shifted their ranges north and are now found in New England coastal habitats where they were previously absent.[169,170] These two species join an assemblage of native and invasive crab species, which are responding to changes in environmental and ecological conditions in different ways. In some locations, purple marsh crabs are benefiting from lower abundances of blue crabs and other predators, in part due to overfishing; this results in population explosions of purple marsh crabs that damage marsh habitats through herbivory (plant eating) and burrowing activities.[171] Because salt marshes provide a range of ecosystem services, including coastal protection, erosion control, water purification, carbon sequestration, and maintenance of fisheries, marsh destruction can negatively impact human communities.[172] Thus, climate impacts to ecosystems can have important consequences for ecosystem services and the people who depend on them.

Key Message 3

Ecosystem Services at Risk

The resources and services that people depend on for their livelihoods, sustenance, protection, and well-being are jeopardized by the impacts of climate change on ecosystems. Fundamental changes in agricultural and fisheries production, the supply of clean water, protection from extreme events, and culturally valuable resources are occurring.

Climate change is affecting the availability and delivery of ecosystem services to society through altered provisioning, regulating, cultural, and supporting services.[95]

A reduced supply of critical provisioning services (food, fiber, and shelter) has clear consequences for the U.S. economy and national security and could create a number of challenges for natural resource managers.[104] Although an extended growing season resulting from phenological shifts may have positive effects on the yield and prices of particular crops,[173] net changes to agricultural productivity will vary regionally (Figure 7.6) and will be affected by other climate change impacts, such as drought and heat stress.[174,175] In addition, early springs with comparatively late (but climatically normal) frosts can directly affect plant growth and seed production and indirectly disrupt ecosystem services such as pollination. By the middle of this century, early onset of spring could occur one out of every three years; however, if the date of last freeze does not change at the same rate, large-scale plant damage and agricultural losses, [176,177,178] as well as changes to natural resource markets,[119] are possible. Shellfish harvests are also projected to decline significantly through the end of the century due to ocean acidification, with cumulative estimated losses of $230 million

under RCP8.5 and $140 million under RCP4.5 (discounted at 3%) (see the Scenario Products section of App. 3 for more information on scenarios).[104]

The degree to which climate change alters species' ranges can create jurisdictional conflict and uncertainty.[97] For example, fisheries management is typically done within defined boundaries and governed by local or international bodies, and terrestrial resource extraction typically occurs on private property or leased public lands with legislated boundaries.[180] Local extinctions and range shifts of marine species have already been documented (Ch. 9: Oceans, KM 2), as species' ranges shift with changing habitat and food conditions. Some species have moved out of historical boundaries and seasonal areas and into places that have no policy, management plan, or regulations in place to address their presence and related human use. Furthermore, unique life histories and genetic resources will likely be lost altogether as range shifts and the spread of invasive species interact with ecological complexity. Examples include loss of genetic diversity and the evolution of traits that increase rates of dispersal.[181,182] Managers may also need to respond to an alteration in the timing of spawning and migration of fish species in order to avoid overly high levels of fish mortality.[183]

Climate change can affect important regulating services such as the capture and storage of carbon,[126] which can help reduce greenhouse

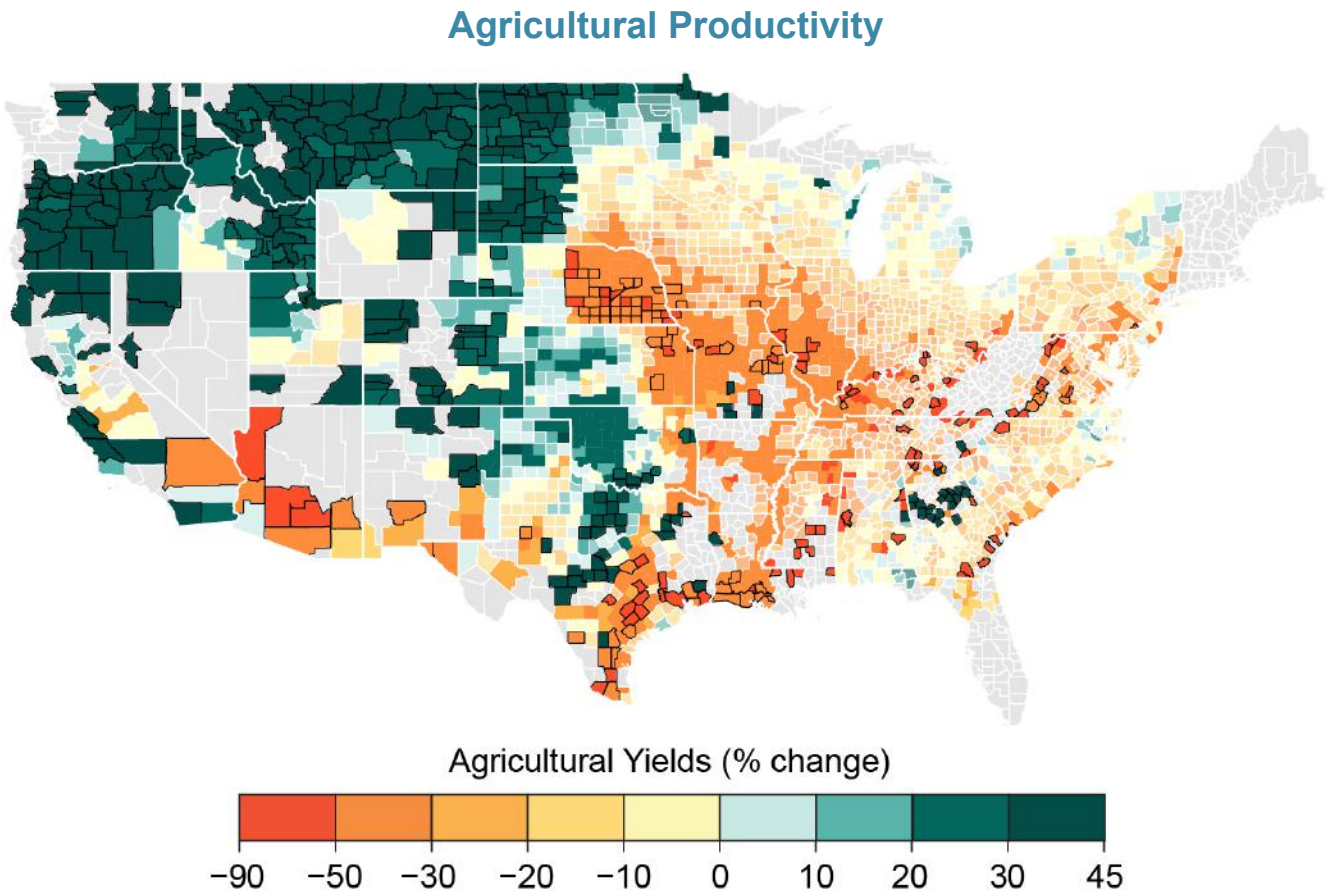


Figure 7.6: The figure shows the projected percent change in the yield of corn, wheat, soybeans, and cotton during the period 2080–2099. Units represent average percent change in yields under the higher scenario (RCP8.5) as compared to a scenario of no additional climate change. Warmer colors (negative percent change) indicate large projected declines in yields; cooler colors (green) indicate moderate projected increases in yields. Source: adapted from Hsiang et al. 2017.[179] Data were not available for the U.S. Caribbean, Alaska, or Hawai'i and U.S.-Affiliated Pacific Islands regions.

gas concentrations in the atmosphere and thereby contribute to climate change mitigation.[184] Climate change impacts, such as changes to the range and abundance of vegetation, to the incidence of wildfire and pest outbreaks, and to the timing and species composition of phytoplankton blooms, can all impact carbon cycling and sequestration (Ch. 5: Land Changes, KM 1; Ch. 6: Forests, KM 2; Ch. 9: Oceans, KM 2; Ch. 29: Mitigation, Box 29.1). Disease regulation is also an important ecosystem service that can be impacted by climate change. Pests and diseases are expected to expand or shift their ranges as the climate warms, and the evolution of immune responses will be important for both human and animal health (Ch. 18: Northeast, KM 4; Ch. 21: Midwest, KM 4; Ch. 26: Alaska, KM 3; Ch. 6: Forests, KM 1; Ch. 14: Human Health, KM 1).[185,186] Other examples of regulating ecosystem services that could be impacted by climate change include coastal protection from flooding and storm surge by natural reefs (Ch. 8: Coastal, KM 2),[187] the supply of clean water (Ch. 3: Water, KM 1)[188] and controls on the timing and frequency of wildfires (Ch. 6: Forests, KM 1).[189]

Some cultural ecosystem services are also at risk from climate change. By the end of the century (2090), cold water recreational fishing days are predicted to decline, leading to a loss in recreational fishing value of $1.7 billion per year under RCP4.5 and $3.1 billion per year under RCP8.5 by 2090.[104] Climate change is also predicted to shorten downhill and cross-country ski seasons.[104] In northwestern Wyoming and western Montana, the cross-country ski season is projected to decline by 20%–60% under RCP4.5 and 60%–100% under RCP8.5 by 2090 (Ch. 22: N. Great Plains, KM 3). Climate change also threatens Indigenous peoples' cultural relationships with ancestral lands (Ch. 15: Tribes, KM 1). In addition, biodiversity and ecosystems are valuable to humans in and of themselves through their "existence value," whereby people derive satisfaction and value simply from knowing that diverse and healthy ecosystems exist in the world.[190] For example, a recent study found that the average U.S. household is willing to pay $33–$73 per year for the recovery or delisting of one of eight endangered or threatened species they studied.[191] However, climate change could have a positive impact on recreational activities that are more popular in warmer weather. For example, demand for biking, beachgoing, and other recreational activities has been projected to increase as winters become milder.[95,192]

Finally, climate change is impacting supporting services, which are the services that make all other ecosystem services possible. Climate change impacts include alterations in primary production and nutrient cycling.[48,193] Novel species assemblages associated with climate change can result in changes to energy and nutrient exchange (for example, altered carbon use in streams as new detritus-feeding or predator communities emerge) within and among ecological communities.[193] Because supporting services underpin all other ecosystem services, climate-induced changes to these services can have profound effects on human well-being.

Key Message 4

Challenges for Natural Resource Management

Traditional natural resource management strategies are increasingly challenged by the impacts of climate change. Adaptation strategies that are flexible, consider interacting impacts of climate and other stressors, and are coordinated across landscape scales are progressing from theory to application. Significant challenges remain to comprehensively incorporate climate adaptation planning into mainstream natural resource management, as well as to evaluate the effectiveness of implemented actions.

Climate change is affecting valued resources and ecosystem services in complex ways, as well as challenging existing management practices. While natural resource management has traditionally focused on maintaining or restoring historical conditions, these goals and strategies may no longer be realistic or effective as the climate changes.[194] Climate-driven changes are most effectively managed through highly adaptive and proactive approaches that are continually refined to reflect emerging and anticipated impacts of climate change (Ch. 28: Adaptation, Figure 28.1).[194] Decision support tools, including scenario planning[195,196,197] and structured decision-making,[198] can help decision-makers explore broad scenarios of risk and develop actions that account for uncertainty, optimize tradeoffs, and reflect institutional capacity.

Systems that are already degraded or stressed from non-climate stressors have lower adaptive capacity and resilience (Ch. 28: Adaptation, KM 3); therefore, some of the most effective actions that managers can take are to strategically restore and conserve areas that support valued species and habitats. However, these actions will be most effective when they consider future conditions in addition to historical targets.[4] New guidance on habitat restoration actions that can help to reduce impacts from climate change[199,200,201] is now being incorporated into regional and local restoration plans (Ch. 24: Northwest, KM 2). Limiting the spread of invasive species can also help maintain biodiversity, ecosystem function, and resilience.[202,203,204] In 2016, the U.S. Federal Government recommended specific management actions for the early detection and eradication of invasive species.[205]

Understanding and reestablishing habitat connectivity across terrestrial, freshwater, and marine systems are other key components in helping ecosystems adapt to changing environmental conditions.[45,46,201,206] Identifying and conserving climate change refugia (that is, areas relatively buffered from climate change that enable persistence) in ecological corridors can help species stay connected.[207,208] For example, areas of particularly cold water have been identified in the Pacific Northwest that, if well-connected and protected from other stressors, could act as critical habitat for temperature-sensitive salmon and trout populations.[209,210,211] More active approaches like assisted migration, whereby species are actively moved to more suitable habitats, and genetic rescue, where genetic diversity is introduced to improve fitness in small populations,[212] may be considered for species that have limited natural ability to move or that face extreme barriers to movement due to habitat fragmentation and development (Ch. 5: Land Changes, "State of the Sector" and KM 2).[124] For any assisted migration, there could be unforeseen and unwanted consequences. Developing policies to analyze and manage the potential consequences of assisted migration would not guarantee successful outcomes, but is likely to minimize unintended consequences.[213,214]

Climate change impacts have been incorporated into national and regional management plans that seek to mitigate harmful impacts and to address future management challenges, while also accounting for other non-climate stressors. Federal agencies with responsibilities for natural resource management are increasingly considering climate change impacts in their management plans, and many have formulated climate-smart adaptation plans for future resource management (such as the National Oceanic and Atmospheric Administration [NOAA], National Park Service [NPS], and U.S. Fish and Wildlife Service [USFWS]).[215,216,217,218,219,220] For example, the National Marine Fisheries Service recognizes climate change as a specific threat to marine resources, has developed regional action plans (e.g., Hare et al. 2016[221]), and is undertaking regional vulnerability analyses to incorporate climate change impacts in decision-making.[129,215,217] Agencies within the Department of the Interior are also increasingly developing and using climate change vulnerability assessments as part of their adaptation planning processes.[222] For example, USFWS has considered climate change in listing decisions, biological opinions, and proposed alternative actions under the Endangered Species Act (e.g., USFWS 2008, 2010[223,224]). In addition, federal agencies have been challenged to develop policies and approaches that consider ecosystem services and related climate impacts within existing planning and decision frameworks.[225] For example, ecosystems can be managed to help mitigate climate change through carbon storage on land and in the oceans (Ch. 29: Mitigation, Box 29.1; Ch. 5: Land Changes, KM 1)[200,226,227] and to buffer ocean acidification,[228] which could help reduce pressure on ecosystems. USFWS has been acquiring and restoring ecosystems to increase biological carbon sequestration since the 1990s.[229]

At the local and regional levels, efforts to restore ecosystems, increase habitat connectivity, and protect ecosystem services are gaining momentum through collaborations among state and tribal entities, educational institutions, nongovernmental organizations, and partnerships. For example, the Great Lakes Climate Adaptation Network, NOAA's Great Lakes Integrated Sciences and Assessments Program, the Huron River Watershed Council, and five Great Lakes cities worked together to develop a vulnerability assessment template that incorporates adaptation and climate-smart information into city planning (Ch. 21: Midwest, Case Study "Great Lakes Climate Adaptation Network"). Significant work remains, however, before climate change is comprehensively addressed in natural resource management at local and national scales. Improved projections of climate impacts at local and regional scales would likely improve ecosystem management, as would predictive models to inform effective adaptation strategies.[230,231,232] Yet such tools are often hampered by a lack of sufficient data at the appropriate scale.[232] In addition, institutional barriers (such as a focus on near-term planning, fixed policies and protocols, jurisdictional restrictions, and an established practice of managing based on historical conditions) have constrained agencies from comprehensively accounting for climate impacts.[194] Finally, more rigorous evaluation of adaptation efforts would allow managers to fully assess the effectiveness of proposed adaptation measures.[194]

Acknowledgments

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Opening Image Credit

Bear catching salmon: Lisa Hupp/U.S. Fish and Wildlife Service.

Traceable Accounts

Process Description

Topics for the chapter were selected to improve the consistency of coverage of the report and to standardize the assessment process for ecosystems and biodiversity. Chapter leads went through the detailed technical input for the Third National Climate Assessment and pulled out key issues that they felt should be updated in the Fourth National Climate Assessment. The chapter leads then came up with an author team with expertise in these selected topics. To ensure that both terrestrial and marine issues were adequately covered, most sections have at least one author with expertise in terrestrial ecosystems and one with expertise in marine ecosystems.

Monthly author calls were held beginning in December 2016, with frequency increasing to every other week as the initial chapter draft deadline approached. During these calls, the team came up with a work plan and fleshed out the scope and content of the chapter. After the outline for the chapter was created, authors reviewed the scientific literature, as well as the technical input that was submitted through the public call. After writing the State of the Sector section, authors pulled out the main findings to craft the Key Messages.

Key Message 1

Impacts on Species and Populations

Climate change continues to impact species and populations in significant and observable ways (*high confidence*). Terrestrial, freshwater, and marine organisms are responding to climate change by altering individual characteristics, the timing of biological events, and their geographic ranges (*likely, high confidence*). Local and global extinctions may occur when climate change outpaces the capacity of species to adapt (*likely, high confidence*).

Description of evidence base

Changes in individual characteristics: Beneficial effects of adaptive capacity depend on adequate genetic diversity within the existing population and sufficient population sizes. In addition, successful adaptive responses require relatively slow or gradual environmental change in relation to the speed of individual or population-level responses.[13] Empirical evidence continues to suggest that plastic changes and evolution have occurred in response to recent climate change[10,11,12,233] and may be essential for species' persistence.[186,234,235] However, adaptation is only possible if genetic diversity has not already been eroded as a result of non-climate related stressors such as habitat loss.[15] Additionally, projections suggest that climate change may be too rapid for some species to successfully adapt.[35,236] Adaptive capacity, and by extension the ability to avoid local or even global extinctions, is likely to vary among species and even populations within species.

Changes in range: Shifts in species' ranges have been documented in both terrestrial and aquatic ecosystems as species respond to climate change.[35,39] Approximately 55% of terrestrial and marine plant and animal species studied in temperate North America have experienced range shifts.[35] Climate change has led to contractions in the latitudinal or elevational ranges of 41% (97 of 238) of studied terrestrial plant and animal species in North America and Hawai'i in the last 50–100 years.[35] Range shifts in terrestrial animal communities average 3.8 miles per decade.[107] In marine

communities, range shifts of up to 17.4 miles per decade have been documented.[17] Planktonic organisms in the water column (that is, passively floating organisms in a body of water) more closely track the trajectory of preferred environmental conditions, resulting in more extensive range shifts; these organisms have exhibited rates of change from 4.3 miles per decade for species with broad environmental tolerances to 61.5 miles per decade for species with low tolerance of environmental change over a 60-year period.[237] Walsh et al. (2015)[38] documented significant changes in the center of distribution over two decades of 43% of planktonic larvae of 45 fish species.

These shifts have been linked to climate velocity—the rate and direction of change in temperature patterns.[30,39,238,239] Marked differences in observed patterns of climate velocity in terrestrial and aquatic ecosystems have been observed.[29,240] Climate velocity in the ocean can be greater than that on land by a factor of seven.[17]

Changes in phenology: In marine and freshwater systems, the transition from winter to spring temperatures is occurring earlier in the year, as evidenced by satellite measures of sea surface temperature dating back to 1981.[23] In addition, the timing of sea ice melt is occurring earlier in the spring at a rate of about 2 days per decade and has advanced by 25–30 days since 1979 in some regions.[24] Shifts in phenology have been well documented in terrestrial, marine, and freshwater systems.[113] As with range shifts, changes to phenology are expected to continue as the climate warms.[114]

Extinction risks: The rate and magnitude of climate impacts can exceed the abilities of even the most adaptable species, potentially leading to tipping points and abrupt system changes. In the face of rapid environmental change, species with limited adaptive capacity may experience local extinctions or even global extinctions.[126,127]

Major uncertainties

Changes in individual characteristics: Species and populations everywhere have evolved in response to reigning climate conditions, demonstrating that evolution will be necessary to survive climate change. Nonetheless, there is very limited evidence for evolutionary responses to recent climate change. As reviewed by Crozier and Hutchings (2014),[10] only two case studies document evolutionary responses to contemporary climate change in fish, as opposed to plasticity without evolution or preexisting adaptation to local conditions, and both cases involved the timing of annual migration.[241,242] In the case of the sockeye salmon, for example, nearly two-thirds of the phenotypic response of an earlier migration date was explained by evolutionary responses rather than individual plastic responses.[241]

Changes in range: Although the evidence for shifting ranges of many terrestrial and aquatic species is compelling, individual species are responding differently to the magnitude and direction of change they are experiencing related to their life history, complex mosaics of microclimate patterns, and climate velocity.[243,244,245,246,247] Additionally, projections of future species distributions under climate change are complicated by the interacting effects of multiple components of climate change (such as changing temperature, precipitation, sea level rise, and so on) and effects from non-climate stressors (such as habitat loss and degradation); these multiple drivers of range shifts can have compounding or potentially opposing effects, further complicating projections of where species are likely to be found in the future.[41]

Description of confidence and likelihood

There is *high confidence* that species and populations continue to be impacted by climate change in significant and observable ways.

There is *high confidence* that terrestrial, freshwater, and marine organisms are *likely* responding to climate change by altering individual characteristics, the timing of biological events, and their geographic ranges.

There is *high confidence* that local and global extinctions are *likely* to occur when climate change outpaces the capacity of species to adapt.

Key Message 2

Impacts on Ecosystems

Climate change is altering ecosystem productivity, exacerbating the spread of invasive species, and changing how species interact with each other and with their environment (*high confidence*). These changes are reconfiguring ecosystems in unprecedented ways (*likely, high confidence*).

Description of evidence base

Primary productivity: Diverse observations suggest that global terrestrial primary production has increased over the latter 20th and early 21st centuries,[48,49,50,51] and climate models project continued increases in global terrestrial primary production over the next century.[130,131] Modest to moderate declines in ocean primary production are projected for most low- to midlatitude oceans over the next century,[143,144,145] but regional patterns of change are less certain.[60,143,145]

Projections also suggest that changes in productivity will not be equal across trophic levels: changes in primary productivity are likely to be amplified at higher levels of the food web;[149,150,151] for example, small changes in marine primary productivity are likely to result in even larger changes to the biomass of fisheries catch.[152]

Changes in phenology: Synchronized timing of seasonal events across trophic levels ensures access to key seasonal food sources,[25,248] particularly in the spring, and is especially important for migratory species dependent on resources with limited availability and for predator–prey relationships.[29] The match–mismatch hypothesis[249] is a mechanism explaining how climate-induced phenological changes in producers and consumers can alter ecosystem food web dynamics.[114] For example, Chevillot et al. (2017)[250] found that reductions in temporal overlap of juvenile fish and their zooplankton prey within estuaries, driven by changes in temperature, salinity, and freshwater discharge rates, could threaten the sustainability of nursery functions and affect the recruitment of marine fishes. Secondary consumers may be less phenologically responsive to climate change than other trophic groups,[114] causing a trophic mismatch that can negatively impact reproductive success and overall population levels by increasing vulnerability to starvation and predation.[16,155] Long-distance migratory birds, which have generally not advanced their phenology as much as lower trophic levels,[113] can be particularly vulnerable.[27] A recent study found that 9 out of 48 migratory bird species examined did not keep pace with the changing spring phenology of plants (termed green-up) in the period 2001–2012.[28] Trophic mismatch and an inability to sufficiently

advance migratory phenology such that arrival remains synchronous with peak resource availability can cause declines in adult survival and breeding success.[28,155]

Invasive species: Changes in habitat and environmental conditions can increase the viability of introduced species and their ability to establish.[69,75,76] Climate change may be advantageous to some nonnative species. Such species are, or could become, invasive, as this advantage might allow them to outcompete and decimate native species and the ecosystem services provided by the native species.

Invasive species' impacts on ecosystems are likely to have a greater negative impact on human communities that are more dependent on the landscape/natural resources for their livelihood and cultural well-being.[251,252] Thus rural, ranching, fishing, and subsistence economies are likely to be negatively impacted. Some of these communities are economically vulnerable (for example, due to low population density, low median income, or reduced tax revenues) and therefore have limited resources and ability to actively manage invasive species.[253,254] Climate change and invasive species have both been recognized as two of the most significant issues faced by natural resource managers.[61,62] For example, the invasive cheatgrass (*Bromus tectorum*) is predicted to increase in abundance with climate change throughout the American West, increasing the frequency of major economic impacts associated with the management and rehabilitation of cheatgrass-invaded rangelands.[255,256] Ecological and economic costs of invasive species are substantial, with global costs of invasive species estimated at over $1.4 trillion annually.[61] Annual economic damages from climate change are complex and are projected to increase over time across most sectors that have been examined (such as coral reefs, freshwater fish, shellfish) (Ch. 29: Mitigation, Figure 29.2).

Species interactions and emergent properties: Human-caused stressors such as land-use change and development can also lead to novel environmental conditions and ecological communities that are further degraded by climate impacts (Ch. 11: Urban, KM 1) .[13,163] Studies of emergent properties have progressed from making general predictions to providing more nuanced evaluations of behavioral mechanisms such as adjusting the timing of activity levels to avoid heat stress [6,81,87] and predation,[88] tolerances to variable temperature fluctuations and water availability,[79,80,82,257] adaptation to changes,[82,258] turnover in community composition,[259,260] and specific traits such as dispersal ability.[67,85]

Changes in community composition vary relative to invasion rates of new species, local extinction, and recruitment and growth rates of resident species, as well as other unknown factors.[260] In some cases, such as Pacific Northwest forests, community turnover has been slow to date, likely due to low exposure or sensitivity to the direct and indirect impacts of climate change,[259] while in other places, like high-latitude systems, dramatic shifts in community composition have been observed.[261] Differential responses within and across communities are expected due to individual sensitivities of community members. For example, as a result of the uncertainties associated with range shifts, the impact of individual species' range shifts on ecosystem structure and function and the potential for the creation of novel community assemblages have medium certainty. The interplay of physical drivers resulting in range shifts and the ways in which interactions of species in new assemblages shape final outcomes affecting ecosystem dynamics is uncertain, although there is more certainty in how ecosystem services will change locally. There is still high uncertainty in the rate and magnitude at which community turnover will occur in many systems; still, there

is widespread agreement of high turnover and major changes in age and size structure with future climate impacts and interactions with other disturbance regimes.[259,260,261]

Climate-induced warming is predicted to increase overlaps between some species that would normally be separated in time. For example, tree host species could experience earlier bud burst, thus overlapping with the larval stage of insect pests; this increase in synchrony between normally disparate species can lead to major pest outbreaks that alter community composition, productivity, ecological functioning, and ecosystem services.[262] Direct climate impacts, such as warmer winters and drought-induced stress on forests, can interact with dynamics of pest populations to render systems more susceptible to damage in indirect ways. In the case of the bark beetle, for example, forests that have experienced drought are more vulnerable to damage from beetle attacks.[138,263] Other potential outcomes of novel species assemblages are changes in energy and nutrient exchange (for example, altered carbon use in streams as new detritus-feeding or predator communities emerge)[193] and respiration[89] within and among ecological communities. Abrupt and surprising changes or the disruption of trophic interactions have the potential for negative and irreversible impacts on food webs and ecosystem productivity that supports important provisioning services including fisheries and forest harvests for food and fiber. Abrupt changes in climate have been observed over geological timescales and have resulted in mass extinctions, decreased overall biodiversity, and ecological communities largely composed of generalists.[67]

Major uncertainties

Primary productivity: There is still high uncertainty in how climate change will impact primary productivity for both terrestrial and marine ecosystems. For terrestrial systems, this uncertainty arises from an incomplete understanding of the impacts of continued carbon dioxide increases on plant growth;[132,133,134] underrepresented nutrient limitation effects;[135] effects of fire[136] and insect outbreaks;[137] and an incomplete understanding of the impacts of changing climate extremes[138,139] on primary production. Direct evidence for declines in marine primary production is limited. The suggestion that phytoplankton pigment has declined in many ocean regions,[55] indicating a decline in primary production, was found to be inconsistent with primary production time series[59] and potentially sensitive to analysis methodology.[56,58,264] Subsequent work accounting for methodological criticisms still argued for a century-scale decline in phytoplankton pigment but acknowledged large uncertainty in the magnitude of this decline and that some areas show marked increases.[54] There is growing consensus for modest to moderate productivity declines at a global scale in the marine realm.[143,144,145] Considerable disagreement remains at regional scales.[143] For both the terrestrial and marine case, however, projections clearly support the potential for marked primary productivity changes.

Phenology: Models of phenology, particularly those leveraging advanced statistical modeling techniques that account for multiple drivers in phenological forecasts,[265] enable extrapolation across space and time, given the availability of gridded climatological and satellite data.[21,266,267,268] However, effective characterization of phenological responses to changes in climate is often constrained by the availability of adequate in situ (ground-based) organismal data. Experimental manipulation of ecological communities may be insufficient to determine sensitivities; for example, E. M. Wolkovich et al. (2012)[269] compared observational studies to warming experiments across four continents and found that warming predicted smaller advances in the timing of flowering and leafing by 8.5- and 4.0-fold, respectively, than what has been observed through long-term observations.

The majority of terrestrial plant phenological research to date has focused on patterns and variability in the onset of spring, with far fewer studies focused on autumn.[270] However, autumn models have large biases in describing interannual variation.[271,272] Additional research is needed on autumnal responses to environmental variation and change, which would greatly expand inferences related to the carbon uptake period, primary productivity, nutrient cycling, species interactions, and feedbacks between the biosphere and atmosphere.[273,274,275,276] While broad-based availability of phenological data has improved greatly in recent years, more extensive, long-term monitoring networks with consistently implemented protocols would further improve scientific understanding of phenological responses to climate change and would better inform management applications.[277]

Invasive species: There is some uncertainty in knowing how much a nonnative species will impact an environment, if and when it is introduced, although there are methods available for estimating this risk.[278,279] For example, the U.S. Department of Agriculture conducts Weed Risk Assessment,[280] and the U.S. Fish and Wildlife Service publishes Ecological Risk Screening Summaries (https://www.fws.gov/fisheries/ans/species_erss_reports.html). New technologies, such as genetic engineering, environmental DNA, and improved detection via satellites and drones, offer promise in the fight against invasive species.[281] New technologies and novel approaches to both invasive species management and mitigation and adapting to climate change could reduce negative impacts to livelihoods, but there is some uncertainty in whether or not the application of new technologies can gain social acceptance and result in practical applications.

Species interactions and emergent properties: Climate change impacts to ecosystem properties are difficult to assess and predict, because they arise from interactions among multiple components of each system, and each system is likely to respond differently. One generalization that can be made arises from fossil records, which show climate-driven mass extinctions of specialists followed by novel communities dominated by generalists.[67] Although there is widespread consensus among experts that novel interactions and ecosystem transitions will result from ecological responses to climate change,[85] these are still largely predicted consequences, and direct evidence remains scarce; thus, estimates of how ecosystem services will change remain uncertain in many cases.[13,67,84,128,159,161,162,163,258,282,283] Modeling and experimental studies are some of the few ways to assess complicated ecological interactions at this time. New and more sophisticated models that can account for multispecies interactions, community composition and structure, dispersal, and evolutionary effects are still needed to assess and make robust predictions about system responses and transitions.[161,258,282]

High uncertainty remains for many species and ecosystems due to a general lack of basic research on baseline conditions of biotic interactions; community composition, structure, and function; and adaptive capacity; as well as the interactive, synergistic, and antagonistic effects of multiple climate and non-climate stressors.[67,128,283] Improved understanding of predator–prey defense mechanisms and tolerances are key to understanding how novel trophic interactions will manifest.[257]

Description of confidence and likelihood

There is *high confidence* that climate-induced changes are occurring within and across ecosystems in ways that alter ecosystem productivity and how species interact with each other and their environment.

There is *high confidence* that such changes can *likely* create mismatches in resources, facilitate the spread of invasive species, and reconfigure ecosystems in unprecedented ways.

Key Message 3

Ecosystem Services at Risk

The resources and services that people depend on for their livelihoods, sustenance, protection, and well-being are jeopardized by the impacts of climate change on ecosystems (*likely, high confidence*). Fundamental changes in agricultural and fisheries production, the supply of clean water, protection from extreme events, and culturally valuable resources are occurring (*likely, high confidence*).

Description of evidence base

Similar to the Third National Climate Assessment, results of this review conclude that climate change continues to affect the availability and delivery of ecosystem services to society through altered agricultural and fisheries production, protection from storms and flooding in coastal zones, a sustainable harvest, pollination services, the spread of invasive species, carbon storage, clean water supplies, the timing and intensity of wildfire, the spread of vector-borne diseases, and recreation.[1,29,104,113,152,284,285]

Provisioning services: Regional changes in critical provisioning services (food, fiber, and shelter) have been observed as range shifts occur. These result in spatial patterns of winners and losers for human communities dependent on these resources. For example, as the distribution of harvestable tree species changes over time in response to climate change, timber production will shift in ways that create disconnects between resource availability and ownership rights.[286]Although fisheries are more often treated as common property resources (with attendant problems related to the overuse and mismanagement of common resources),[287] disconnects emerge with respect to the definitions of management units and jurisdictional conflict and uncertainty.[97] Shifting distribution patterns can potentially affect access to both harvested and protected natural resources, cultural services related to the rights of Indigenous peoples and to recreation, and the aesthetic appreciation of nature in general (Ch. 15: Tribes, KM 1).[288]

Additionally, changes in physical characteristics in response to climate change can impact ecosystem services. In the ocean, the combination of warmer water and less dissolved oxygen can be expected to promote earlier maturation, smaller adult body size, shorter generation times, and more boom–bust population cycles for large numbers of fish species.[289] These changes would have profound ecosystem effects, which in turn would affect the value of ecosystem services and increase risk and volatility in certain industries.

Altered phenology can also impact ecosystem services. Based on standardized indices of the timing of spring onset,[21] 2012 saw the earliest spring recorded since 1900 across the United States.[21,290] Much of the central and eastern parts of the contiguous United States experienced spring onset as much as 20 to 30 days ahead of 1981–2010 averages, and accelerated blooming in fruiting trees was followed by a damaging, but climatically normal, hard freeze in late spring, resulting in widespread reductions in crop productivity.[20] Mid-century forecasts predict that spring events similar to that of 2012 could occur as often as one out of every three years; because last freeze dates may not change at the same rate, more large-scale plant tissue damage and agricultural losses are possible.[177,178] Early springs with episodic frosts not only directly affect plant growth and seed production but can also indirectly alter ecosystem functions such as pollination.[291,292]

Potential asynchronies may impact some pollination services, although other pollinator–plant relationships are expected to be robust in the face of shifting phenology.[291,293,294,295] For example, broad-tailed hummingbirds in Colorado and Arizona have advanced their arrival date between 1975 and 2011, but not sufficiently to track changes in their primary nectar sources.

Regulating services: Average carbon storage in the contiguous United States is projected to increase by 0.36 billion metric tons under RCP4.5 and 3.0 billion metric tons under RCP8.5.[104] However, carbon storage is projected to decrease for U.S. forests (Ch. 6: Forests, KM 2). Increases in overall carbon storage are projected for the Northwest, and decreases are projected for the Northeast and Midwest.[104] Furthermore, shorter winters and changing phenology may affect the incidence and geographic extent of vector-borne diseases (Ch. 14: Human Health, KM 1).[284,296,297,298,299] Other examples of regulating ecosystem services that are impacted by climate include coastal protection from flooding and storm surge by natural reefs (Ch. 8: Coastal, KM 2),[187] the supply of clean water (Ch. 3: Water, KM 1),[188] and controls on the timing and frequency of wildfires (Ch. 6: Forests, KM 1).[189]

Cultural services: Climate change is expected to impact recreation and tourism in the United States, as well as cultural resources for Indigenous peoples (Ch. 15: Tribes, KM 1).[95,104,192] While some changes may be positive (such as increased biking and hiking access in colder seasons or cold-weather areas), other changes will have negative impacts (such as reduced skiing opportunities).[95,104]

Supporting services: Climate change is impacting supporting services, which are the services that make all other ecosystem services possible. Climate change impacts include alterations in primary production and nutrient cycling.[48,193]

Major uncertainties

One of the major challenges to understanding changes in ecosystem services due to climate change arises from matching the scale of the ecosystem change to the scale at which humans are impacted. Local conditions may vary greatly from changes expected at larger geographic scales. This uncertainty can work in both directions: local estimates of changes in ecosystems services can be overestimated when local impacts of climate change are less than regional-scale impacts. However, estimates of local impacts on ecosystem services can be *under*estimated when local impacts of climate change exceed regional projections. Another major source of uncertainty is related to the emergent properties of ecosystems related to climate change. Since observation of

human impacts of these emergent ecosystem properties is lacking, it is difficult to predict how humans will be impacted and how they might adapt.

Description of confidence and likelihood

There is *high confidence* that the resources and services that people depend on for livelihoods, sustenance, protection, and well-being are *likely* jeopardized by the impacts of climate change on ecosystems.

There is *high confidence* that fundamental changes in agricultural and fisheries production, the supply of clean water, protection from extreme events, and culturally valuable resources are *likely* occurring.

Key Message 4

Challenges for Natural Resource Management

Traditional natural resource management strategies are increasingly challenged by the impacts of climate change (*high confidence*). Adaptation strategies that are flexible, consider interacting impacts of climate and other stressors, and are coordinated across landscape scales are progressing from theory to application. Significant challenges remain to comprehensively incorporate climate adaptation planning into mainstream natural resource management, as well as to evaluate the effectiveness of implemented actions (*high confidence*).

Description of evidence base

Climate change is increasingly being recognized as a threat to biodiversity and ecosystems. For example, a recently developed threat classification system for biodiversity[300] has been adopted by the International Union for Conservation of Nature, which stands in contrast to previous frameworks that did not include climate change as a threat.[301] Moving away from traditional management strategies that aim to retain existing species and ecosystems and implementing climate-smart management approaches are likely to be the most effective ways to conserve species, ecosystems, and ecosystem services in the future.[194]

Ecosystem-based management strategies, where decisions are made at the ecosystem level,[217] and programs that consider climate change impacts along with other human-caused stressors are becoming more established and seek to optimize benefits among diverse societal goals.[302] A number of regional to national networks have been implemented, including the Department of the Interior's (DOI) Climate Adaptation Science Centers[303] and the NOAA Regional Integrated Sciences and Assessment Programs,[304] that bring together multiple stakeholders to develop approaches for dealing with climate change. Landscape Conservation Cooperatives (LCCs) were established by DOI Secretarial Order 3289 in 2009 to provide transboundary support and science capacity for adaptive resource management. The U.S. Fish and Wildlife Service (Service) is no longer providing dedicated staff and funding to support the governance and operations of the 22 LCCs, consistent with its FY2018 and FY2019 budget requests. The Service will continue to support cooperative landscape conservation efforts as an equal partner, working with states and other partners on priority conservation and management issues. Federal and state agencies with responsibilities for natural resources have begun to implement proactive and climate-smart management

approaches. Recent examples (within the last 10 years) include the development of the National Marine Fisheries Service's Climate Science Strategy[215,217] and its commitment to ecosystem-based fisheries management;[216] the National Park Service's Climate Change Response Program;[305] the Forest Adaptation Planning and Practices collaborative, led by the Northern Institute of Applied Climate Science;[306] the National Fish, Wildlife and Plants Climate Adaptation Strategy;[218] the Southeast Conservation Adaptation Strategy,[307] initiated by states of the Southeastern Association of Fish and Wildlife Agencies, the federal Southeast Natural Resource Leaders Group, the Southeast and Caribbean Landscape Conservation Cooperatives, and the Southeast Aquatic Resources Partnership; and a range of individual state plans.[302] These newly formed collaborative programs better account for the various climate impacts on, and interactions between, ecosystem components, while optimizing benefits among diverse societal goals.

In addition, federal agencies are developing policies and approaches that consider ecosystem services and related climate impacts within existing planning and decision frameworks.[225] For example, NOAA's Fisheries Ecosystem-Based Fisheries Management Policy specifically considers climate change and ecosystem services. By framing management strategies and actions within an ecosystem services context, communication about the range of benefits derived from biodiversity and natural ecosystems can be improved, and managers, policymakers, and the public can better envision decisions that support climate adaptation. Restoration efforts can also help conserve important ecosystem services (Ch. 21: Midwest, Figure 21.7).

An example of an effective, collaborative effort to manage climate impacts took place in Puerto Rico during a recent drought. In order to better manage the impacts of the drought on the environment, people, and water resources, Puerto Rico developed a special task force composed of government officials, federal partners, and members of academia to evaluate the progression, trends, and effects of drought in the territory. Weekly reports from the task force provided recommended actions for government officials and updated the public about the drought (Ch. 20: U.S. Caribbean, Box 20.3).

Changes in Individual characteristics: Maintaining habitat connectivity is important to ensure gene flow among populations and maintain genetic diversity, which provides the platform for evolutionary change. Additionally, assisted migration can be used to increase genetic diversity for less mobile species, which is important to facilitate evolutionary changes.[213]

Changes in range: Climate-induced shifts in plant and animal populations can be most effectively addressed through landscape-scale and ecosystem-based conservation and management approaches. Increasing habitat connectivity for terrestrial, freshwater, and marine systems is a key climate adaptation action that will enable species to disperse and follow physiological niches as environmental conditions and habitats shift.[206] More active approaches like seed sourcing and assisted migration may be considered for planted species or those with limited natural dispersal ability.[308] However, for any assisted migration, there could be unforeseen and unwanted consequences. Although a provision to analyze and manage the potential consequences of assisted migration would not guarantee successful outcomes, developing such policies is warranted toward minimizing unintended consequences.[213,214] Systems that are already degraded or stressed from non-climate factors will have lower adaptive capacity and resilience to climate change impacts; therefore, restoration and conservation of land, freshwater, and marine areas that support valued

species and habitats are key actions for natural resource managers to take. In addition, climate change refugia—areas relatively buffered from climate change that enable persistence—have become a focus of conservation and connectivity efforts to maintain highly valued vulnerable ecosystems and species in place as long as possible.[207,208]

Changes in phenology: Direct management of climate-induced phenological shifts or mismatches is challenging, as managers have few if any direct measures of control on phenology.[248] However, research into how species' phenologies are changing has the potential to support improved conservation outcomes by identifying high-priority phenological periods and informing changes in management actions accordingly. In Vermont grassland systems, for example, research on grassland bird nesting phenology identified the timing of haying as a critical stressor. In response, the timing of haying has been modified to accommodate the nesting phenology of several declining species, including the bobolink, demonstrating the potential for phenological data to support a successful conservation program.[309,310] Such monitoring and research efforts will become increasingly important as climate change results in further phenological shifts. Managing for phenological heterogeneity can also be an effective bet-hedging strategy to manage for a wide range of potential changes.[248]

Invasive species: Focusing efforts on the prevention, eradication, and control of invasive species and the implementation of early detection and rapid response (EDRR) can be considered an adaptation strategy to help maintain healthy ecosystems and preserve biodiversity such that natural systems are more resistant and resilient to climate change and extreme weather events.[202,203] Once an invasive species is established, EDRR is much more effective than efforts to control invasive species after they are widely established.[205] The current U.S. National Invasive Species Council Management Plan[311] recognizes the stressors of land-use change and climate change and calls for an assessment of national EDRR capabilities.

Major uncertainties

Better predictive models are necessary to create effective adaptation strategies, but they can be hampered by a lack of sufficient data to adequately incorporate important biological mechanisms and feedback loops that influence climate change responses.[232] This can be most effectively addressed if resource management approaches and monitoring efforts increasingly expand programs, especially at the community or ecosystem level, to detect and track changes in species composition, interactions, functioning, and tipping points, as well as to improve model inputs.[312,313,314]

Changes in individual characteristics: Although genetic diversity is important for evolution and potentially for increasing the fitness of individuals, it does not guarantee that a species will adapt to future environmental conditions. Failure to adapt may occur when a species or population lacks genetic variability in a particular trait that is under selection (such as heat tolerance) as a result of climate change,[7] despite having high overall genetic diversity.

Changes in Range: Although potential strategies for adaptation to range shifts can be readily identified, the lack of experience implementing these approaches to meet this issue results in uncertainty in the efficacy of different approaches. Another big uncertainty is the incomplete information on the ecology and responses of species and ecosystems to climate change.

Changes in phenology: Phenological sensitivity may also be an important component of organismal adaptive capacity[315] and thus species' vulnerability to climate change, although additional research is required before resource managers can utilize known relative vulnerabilities to prioritize management activities.

Invasive species: There is some uncertainty in the optimal management approach for a given species and location. Best practices for management actions are often context specific; one approach will not fit all scenarios. Management of climate change and invasive species needs to explore such variables as the biology of the target species, the time of year or day for maximizing effectiveness, the ecological and sociocultural context, legal and institutional frameworks, and budget constraints and timeliness.[281]

Description of confidence and likelihood

There is *high confidence* that traditional natural resource management strategies are increasingly challenged by the impacts of climate change.

There is *high confidence* that adaptation strategies that are flexible, consider the emerging and interactive impacts of climate and other stressors, and are coordinated across local and landscape scales are progressing from theory to application.

There is *high confidence* that significant challenges remain to comprehensively incorporate climate adaptation planning into mainstream natural resource management, as well as to evaluate the effectiveness of implemented actions.

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8 Coastal Effects

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8 Coastal Effects

Natural "green barriers" help protect this Florida coastline and infrastructure from severe storms and floods.

Key Message 1

Coastal Economies and Property Are Already at Risk

America's trillion-dollar coastal property market and public infrastructure are threatened by the ongoing increase in the frequency, depth, and extent of tidal flooding due to sea level rise, with cascading impacts to the larger economy. Higher storm surges due to sea level rise and the increased probability of heavy precipitation events exacerbate the risk. Under a higher scenario (RCP8.5), many coastal communities will be transformed by the latter part of this century, and even under lower scenarios (RCP4.5 or RCP2.6), many individuals and communities will suffer financial impacts as chronic high tide flooding leads to higher costs and lower property values. Actions to plan for and adapt to more frequent, widespread, and severe coastal flooding would decrease direct losses and cascading economic impacts.

Key Message 2

Coastal Environments Are Already at Risk

Fisheries, tourism, human health, and public safety depend on healthy coastal ecosystems that are being transformed, degraded, or lost due in part to climate change impacts, particularly sea level rise and higher numbers of extreme weather events. Restoring and conserving coastal ecosystems and adopting natural and nature-based infrastructure solutions can enhance community and ecosystem resilience to climate change, help to ensure their health and vitality, and decrease both direct and indirect impacts of climate change.

Key Message 3

Social Challenges Intensified

As the pace and extent of coastal flooding and erosion accelerate, climate change impacts along our coasts are exacerbating preexisting social inequities, as communities face difficult questions about determining who will pay for current impacts and future adaptation and mitigation strategies and if, how, or when to relocate. In response to actual or projected climate change losses and damages, coastal communities will be among the first in the Nation to test existing climate-relevant legal frameworks and policies against these impacts and, thus, will establish precedents that will affect both coastal and non-coastal regions.

Executive Summary

The Coasts chapter of the Third National Climate Assessment, published in 2014, focused on coastal lifelines at risk, economic disruption, uneven social vulnerability, and vulnerable ecosystems. This Coastal Effects chapter of the Fourth National Climate Assessment updates those themes, with a focus on integrating the socioeconomic and environmental impacts and consequences of a changing climate. Specifically, the chapter builds on the threat of rising sea levels exacerbating tidal and storm surge flooding, the state of coastal ecosystems, and the treatment of social vulnerability by introducing the implications for social equity.

U.S. coasts are dynamic environments and economically vibrant places to live and work. As of 2013, coastal shoreline counties were home to 133.2 million people, or 42% of the population.[1] The coasts are economic engines that support jobs in defense, fishing, transportation, and tourism industries; contribute substantially to the U.S. gross domestic product;[1] and serve as hubs of commerce, with seaports connecting the country with global trading partners.[2] Coasts are home to diverse ecosystems such as beaches, intertidal zones, reefs, seagrasses, salt marshes, estuaries, and deltas[3,4,5] that support a range of important services including fisheries, recreation, and coastal storm protection. U.S. coasts span three oceans, as well as the Gulf of Mexico, the Great Lakes, and Pacific and Caribbean islands.

The social, economic, and environmental systems along the coasts are being affected by climate change. Threats from sea level rise (SLR) are exacerbated by dynamic processes such as high tide and storm surge flooding (Ch. 19: Southeast, KM 2),[6,7,8] erosion (Ch. 26: Alaska, KM 2),[9] waves and their effects,[10,11,12,13] saltwater intrusion into coastal aquifers and elevated groundwater tables (Ch. 27: Hawai'i & Pacific Islands, KM 1; Ch. 3: Water, KM 1),[14,15,16,17] local rainfall (Ch. 3: Water, KM 1),[18] river runoff (Ch. 3: Water, KM 1),[19,20] increasing water and surface air temperatures (Ch. 9: Oceans, KM 3),[21,22] and ocean acidification (see Ch. 2: Climate, KM 3 and Ch. 9: Oceans, KM 1, 2, and 3 for more information on ocean acidification, hypoxia, and ocean warming).[23,24]

Although storms, floods, and erosion have always been hazards, in combination with rising sea levels they now threaten approximately $1 trillion in national wealth held in coastal real estate[25] and the continued viability of coastal communities that depend on coastal water, land, and other resources for economic health and cultural integrity (Ch. 15: Tribes, KM 1 and 2).

Impacts of the 2017 Hurricane Season

Quintana Perez dumps water from a cooler into floodwaters in the aftermath of Hurricane Irma in Immokalee, Florida. *From Figure 8.6 (Photo credit: AP Photo/Gerald Herbert).*

State of the Coasts

U.S. coasts are dynamic environments and economically vibrant places to live and work. As of 2013, coastal shoreline counties were home to 133.2 million people, or 42% of the population.[1] The coasts are economic engines that support jobs in defense, fishing, transportation, and tourism industries; contribute substantially to the U.S. gross domestic product (GDP; Table 8.1);[1,26] and serve as hubs of commerce, with seaports connecting the country with global trade partners.[2] Coasts are home to diverse ecosystems such as beaches, intertidal zones, reefs, seagrasses, salt marshes, estuaries, and deltas[3,4,5] that support a range of important services including fisheries, recreation, and coastal storm protection. U.S. coasts span three oceans as well as the Gulf of Mexico, the Great Lakes, and Pacific and Caribbean islands.

The social, economic, and environmental systems along the coasts are being affected by climate change. Threats from sea level rise (SLR) are exacerbated by dynamic processes such as high tide and storm surge flooding (Ch. 19: Southeast, KM 2),[6,7,8] erosion (Ch. 26: Alaska, KM 2),[9] waves and their effects,[10,11,12,13] saltwater intrusion into coastal aquifers and elevated groundwater tables (Ch. 27: Hawai'i & Pacific Islands, KM 1; Ch. 3: Water, KM 1),[14,15,16,17] local rainfall (Ch. 3: Water, KM 1),[18] river runoff (Ch. 3: Water, KM 1),[19,20] increasing water and surface air temperatures (Ch. 9: Oceans, KM 3),[21,22] and ocean acidification (see Ch. 2: Climate, KM 3 and Ch. 9: Oceans, KM 1, 2, and 3 for more information on ocean acidification, hypoxia, and ocean warming).[23,24]

Collectively, these threats present significant direct costs related to infrastructure.[27,28] The more than 60,000 miles of U.S. roads and bridges in coastal floodplains are already demonstrably vulnerable to extreme storms and hurricanes that cost billions in repairs.[29] The national average increase in the Special Flood Hazard Area by the year 2100 may approach 40% for riverine and coastal areas if shoreline recession is assumed, and 45% for riverine and coastal areas if fixed coastlines are assumed.[30] Additionally, indirect economic costs (such as lost business) and adverse sociopsychological impacts have the potential to negatively affect citizens and their communities.[31,32,33] People exposed to weather- or climate-related disasters have been shown to experience mental health impacts including depression, post-traumatic stress disorder, and anxiety, all of which often occur simultaneously;

Economic Importance of U.S. Coastal Areas

Region	Employment		GDP		Population		% Land Area
	Millions	% of US	$Trillions	% of US	Millions	% of US	
United States	134.0		$16.7		316.5		
All Coastal States	109.2	81.5%	$13.9	83.7%	257.9	81.5%	57.0%
Coastal Zone Counties	56.2	42.0%	$8.0	48.0%	133.2	42.1%	19.6%
Shore-Adjacent Counties	50.2	37.5%	$7.2	43.2%	118.4	37.4%	18.1%

Table 8.1: The coast is a critical component of the U.S. economy. This table shows U.S. employment, GDP, population, and land area compared to coastal areas as of 2013. "Coastal zone counties" comprise shore-adjacent counties plus non-shore-adjacent counties. For more complete definitions, see: http://www.oceaneconomics.org/Market/coastal/coastal_geographies.aspx. Source: Kildow et al. 2016[1]

furthermore, among those most likely to suffer these impacts are some of society's most vulnerable populations, including children, the elderly, those with preexisting mental illness, the economically disadvantaged, and the homeless (Ch. 14: Human Health, KM 1 and 2).[34]

Although storms, floods, and erosion have always been hazards, in combination with rising sea levels they now threaten approximately $1 trillion in national wealth held in coastal real estate (Figure 8.1)[25] and the continued viability of coastal communities that depend on coastal water, land, and other resources for economic health and cultural integrity (Ch. 15: Tribes, KM 1 and 2). The effects of the coastal risks posed by a changing climate already are and will continue to be experienced in both intersecting and distinct ways, and coastal areas are already beginning to take actions to address and ameliorate these risks (Figure 8.2).

Cumulative Costs of Sea Level Rise and Storm Surge to Coastal Property

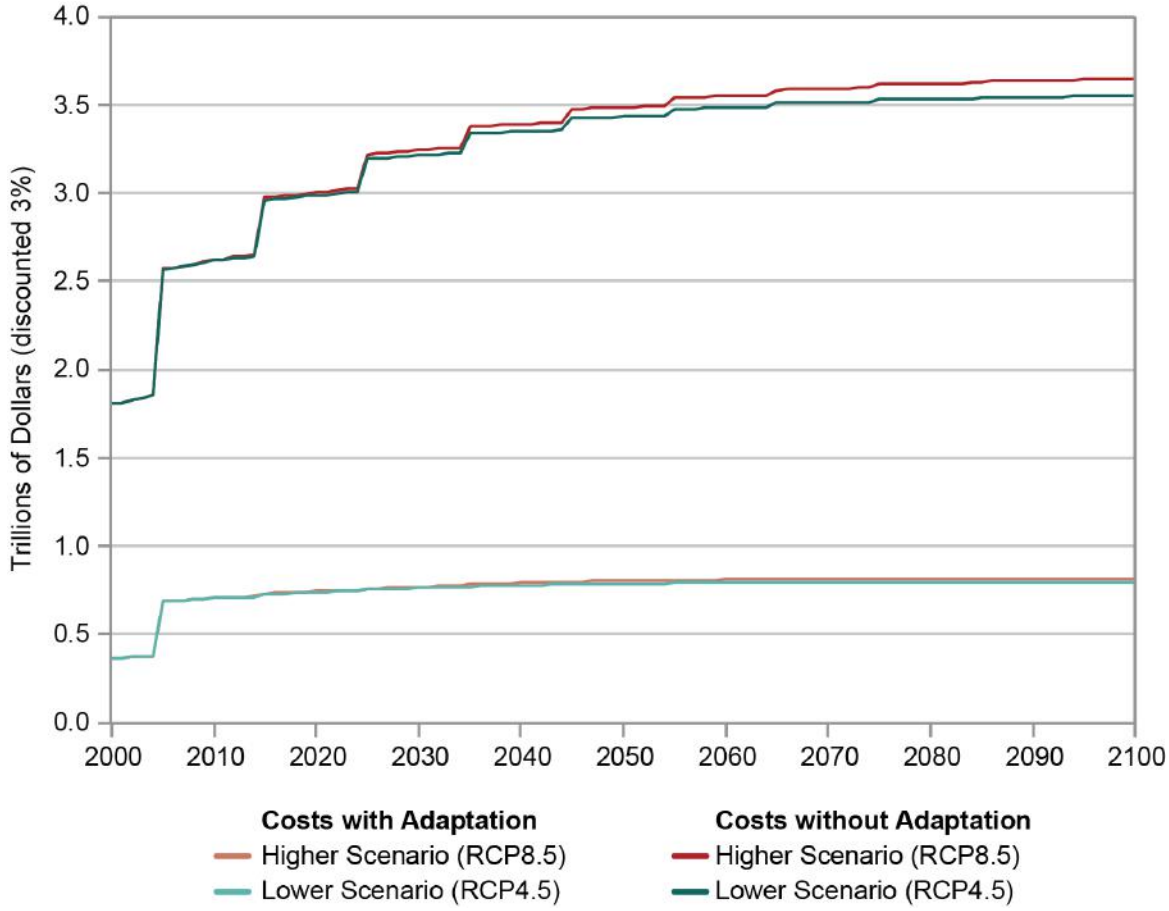

Figure 8.1: This figure shows that cumulative damages (in 2015 dollars) to coastal property across the contiguous United States would be significantly reduced if protective adaptation measures were implemented, compared to a scenario where no adaptation occurs. Without adaptation, cumulative damages under the higher scenario (RCP8.5) are estimated at $3.6 trillion through 2100 (discounted at 3%), compared to $820 billion in the scenario where cost-effective adaptation measures are implemented. Under the lower scenario (RCP4.5), costs without adaptation are reduced by $92 billion relative to RCP8.5 and are $800 billion with adaptation. Note: The stepwise nature of the graph is due to the fact that the analysis evaluates storm surge risks every 10 years, beginning in 2005. Source: adapted from EPA 2017.[35]

Regional Coastal Impacts and Adaptation Efforts

	Impact	Adaptation Efforts
Northeast	Recurrent coastal flooding	The cities of Binghamton, New York, and Boston, Massachusetts, promote the use of green infrastructure to build resilience, particularly in response to flooding risk.
Southeast	Sea level rise	Charleston, South Carolina, has developed a Sea Level Rise Strategy that plans for 50 years out based on moderate sea level rise scenarios, reinvests in infrastructure, develops a response plan, and increases readiness. As of 2016, the City of Charleston has spent or set aside $235 million to complete ongoing drainage improvement projects to prevent current and future flooding.
Midwest	Multiple stressors	The Great Lakes Climate Action Network (GLCAN) is a regional, member-driven peer network of local government staff who work together to identify and act on the unique climate adaptation challenges of the Great Lakes region. GLCAN is working with the Huron River Watershed Council and five Great Lakes cities (Ann Arbor, Dearborn, Bloomington, Indianapolis, and Cleveland) to develop a publicly available universal vulnerability assessment template that mainstreams the adaptation planning process and results in the integration of climate-smart and equity-focused information into all types of city planning.
Northwest	Aquatic species vulnerabilities	In the Yakima Basin, irrigators, conservation groups, and state and federal agencies worked together to replenish the diminished tributary flows to bolster the salmon runs and riparian habitat during the 2015 drought.
Southwest	Storm surge	In 2016, residents of the nine counties of the San Francisco Bay voted in favor of Measure AA, which provides funding for wetlands restoration to naturally reduce risks of flooding and inundation due to sea level rise and storm surge.
Southern Great Plains	Critical infrastructure damage	The Texas Coastal Resiliency Master Plan promotes coastal resilience, defined as the ability of coastal resources and coastal infrastructure to withstand natural or human-induced disturbances and quickly rebound from coastal hazards. This definition encompasses the two dimensions of resilience: 1) taking actions to eliminate or reduce significant adverse impacts from natural and human-induced disturbances, and 2) responding effectively in instances when such adverse impacts cannot be avoided. The Plan will be updated regularly to assess changing coastal conditions and needs and to determine the most suitable way to implement the appropriate coastal protection solutions.
Alaska	Recurrent coastal flooding	The people of Shaktoolik developed and undertook an initiative to build a community-driven, mile-long and seven-foot-high berm made out of driftwood and gravel to protect itself from flooding and erosion during storm episodes.
Hawai'i and U.S.-Affiliated Pacific Islands	Multiple stressors	Adaptation options in Hawai'i and the U.S.-Affiliated Pacific Islands are unique to their island context and more limited than in continental settings. Current adaptation examples include policy initiatives and adaptation programs, such as the accreditation of the Secretariat of the Pacific Regional Environment Programme to the Green Climate Fund; the passage of the Hawai'i Climate Adaptation Initiative Act; and the creation of separate climate change commissions for the City and County of Honolulu.
U.S. Caribbean	Coastal erosion	In Puerto Rico, the U.S. Fish and Wildlife Service and Puerto Rico Department of Natural and Environmental Resources have funded wetlands and dune restoration projects at various sites along the coast of Puerto Rico as non-structural solutions to coastal flooding and beach erosion.

Figure 8.2: The figure shows selected coastal effects of climate change in several coastal regions of the United States. See the online version of this figure at http://nca2018.globalchange.gov/chapter/8#fig-8-2 for additional examples. Source: NCA4 Regional Chapters.

Key Message 1

Coastal Economies and Property Are Already at Risk

America's trillion-dollar coastal property market and public infrastructure are threatened by the ongoing increase in the frequency, depth, and extent of tidal flooding due to sea level rise, with cascading impacts to the larger economy. Higher storm surges due to sea level rise and the increased probability of heavy precipitation events exacerbate the risk. Under a higher scenario (RCP8.5), many coastal communities will be transformed by the latter part of this century, and even under lower scenarios (RCP4.5 or RCP2.6), many individuals and communities will suffer financial impacts as chronic high tide flooding leads to higher costs and lower property values. Actions to plan for and adapt to more frequent, widespread, and severe coastal flooding would decrease direct losses and cascading economic impacts.

Due to sea level rise (SLR), coastal storms and high tides have amplified coastal flooding and erosion impacts, and this trend will continue into the future, with some regions more vulnerable than others (Ch. 2: Climate, KM 9).[6,7,8,9,36,37,38] High tide flooding is already forcing some East Coast cities to install costly pump stations to frequently clear floodwaters from the streets (such as Miami Beach, as shown in Figure 8.3) (see also Ch. 19: Southeast, KM 2) and to mobilize emergency responders to routinely close flooded streets. Along with increases in tidally driven flooding, storm surges are higher due to SLR.[36,39,40] Warmer air temperatures have increased the probability of heavy precipitation events,[41,42,43] permafrost thawing, and earlier season sea ice loss, leading to increased erosion over significant miles of coastline (Ch. 26: Alaska, KM 2). The severity of compound events—the coupling of surge, discharge from rivers, and heavy precipitation—has increased in many coastal cities (Ch. 19: Southeast, KM 2; Ch. 3: Water, KM 2).[18,19] In addition, modeling suggests that tropical cyclone intensity will increase,[40,44,45] which would lead to greater damage upon landfall. Collectively, these factors already threaten coastal economies, public safety, and well-being, and continued growth and development along the coast increase the risk to more people and infrastructure.

Even under a very low scenario (RCP2.6) (see the Scenario Products section of App. 3 for more on scenarios), projections indicate that the frequency, depth, and extent of both high tide and more severe, damaging coastal flooding will increase rapidly in the coming decades.[7,8,36,46,47,48] With rapid ice loss from Greenland and Antarctica under the higher scenario (RCP8.5), an Extreme scenario of global sea level rising upwards of 8 feet by 2100 is a possibility.[36,37,49,50,51,52] Under this rise, the average daily high tide would exceed the current 100-year (1% annual chance) coastal water level event in most U.S. coastal locations.[8,39,53] Because these low-probability, high-consequence risks cannot be ruled out, a robust risk management approach to future planning would involve their consideration.

Coastal property owners are likely to bear costs from SLR and storm surge, including those associated with property abandonment; residual storm damages; protective adaptation measures, such as property elevation; beach nourishment; and shoreline armoring.[35] The potential for future losses is great, with continued and often expensive development at the coasts increasing exposure (Ch. 5: Land Changes, KM 2).[54,55] Shoreline counties hold 49.4 million housing units, while homes

Flooding Impacts in Miami Beach

Figure 8.3: Tidewater is pumped back into a canal near the Venetian Causeway entrance from Purdy Avenue, where the seawall is also being raised, during a seasonal king tide in Miami Beach, Florida, in 2016. Photo credit: Max Reed/The New York Times/Redux.

and businesses worth at least $1.4 trillion sit within about 1/8th mile of the coast.[56] Flooding from rising sea levels and storms is likely to destroy, or make unsuitable for use, billions of dollars of property by the middle of this century, with the Atlantic and Gulf coasts facing greater-than-average risk compared to other regions of the country.[57,58,59] Recent economic analysis finds that under a higher scenario (RCP8.5), it is likely (a 66% probability, which corresponds to the Intermediate-Low to Intermediate sea level rise scenarios) that between $66 billion and $106 billion worth of real estate will be below sea level by 2050; and $238 billion to $507 billion, by 2100.[60]

These market impacts have the potential to influence property developers, lenders, servicers, mortgage insurers, and the mortgage-backed securities industry.[58,61] Coastal property and infrastructure losses cascade into threats to personal wealth and could affect the economic stability of local governments, businesses, and the broader economy.[62] Some coastal property owners are dependent on recouping losses from private or public insurance policies, and there are few private flood insurance policies currently available.[63,64] Mortgage holders located within the federally designated Special Flood Hazard Area defined by the Federal Emergency Management Agency are required to purchase flood insurance, which is almost always obtained through the National Flood Insurance Program (NFIP). Losses generated by the NFIP create substantial financial exposure for the Federal Government and U.S. taxpayers.[65,66] There are already indications in places like Atlantic City, New Jersey, and Norfolk, Virginia,[58,67] that homes subject to recurring flooding may become unsellable. The impacts of Hurricanes Harvey, Irma, and Maria in 2017 will only exacerbate the NFIP losses. (For more information on the 2017 Atlantic hurricane season, see Ch. 2: Climate, Box 2.5.) Additionally, diminished real estate values are likely to result in lower tax revenues and reduced community services (Ch. 28: Adaptation, KM 5).[68,69]

In addition to private property risks, coastal infrastructure, such as roads, bridges, tunnels, and pipelines, provides important lifelines between coastal and inland communities, meaning that damage to this infrastructure results in cascading costs and national impacts (Ch. 12: Transportation, KM 1 and 2).[70] Oil and gas from critical energy infrastructure along the coast is distributed to the entire nation.[71,72] Similarly, the entire country depends on coastal seaports for access to goods and services, as they handle 99% of overseas trade (Ch. 12: Transportation, KM 1). Incorporating adaptation into infrastructure upgrades will be expensive. For instance, the estimated cost to elevate and retrofit the major commercial ports of California (such as San Diego, Los Angeles/Long Beach, San Francisco) to adapt to 6 feet of SLR is $9–$12 billion.[73] Investing in these interconnected lifelines would support community stability and the Nation's economy (Ch. 3: Water, KM 2; Ch. 11: Urban, KM 3; Ch. 17: Complex Systems, KM 1 and 3).[70]

Key Message 2

Coastal Environments Are Already at Risk

Fisheries, tourism, human health, and public safety depend on healthy coastal ecosystems that are being transformed, degraded, or lost due in part to climate change impacts, particularly sea level rise and higher numbers of extreme weather events. Restoring and conserving coastal ecosystems and adopting natural and nature-based infrastructure solutions can enhance community and ecosystem resilience to climate change, help to ensure their health and vitality, and decrease both direct and indirect impacts of climate change.

Coastal ecosystems such as estuaries, deltas, marshes, mangroves, seagrasses, beaches, and reefs provide valuable benefits to the economy and society.[35] They support fisheries, reduce shoreline erosion from waves, improve water quality, and create valuable recreation opportunities.[74] Between 2004 and 2009, it was estimated that U.S. coastal wetland environments have been lost at an average rate of about 80,160 acres per year, with 71% of coastal wetland loss occurring in the Gulf of Mexico.[75] At this rate, by 2100 the United States will have lost an additional 16% of coastal wetlands.[75] Sea level rise in the Atlantic is contributing to the declining health and integrity of Atlantic marshes. Marsh degradation is expected to occur faster in the Atlantic than in the Pacific due to the higher SLR expected along the U.S. Atlantic coast.[76,77]

Coastal wetlands generate climate mitigation benefits by serving as natural sinks for atmospheric carbon dioxide.[78,79,80] As these ecosystems are degraded or lost, their carbon uptake potential will be diminished and their stored carbon potentially released. In addition, wetlands are a first line of natural defense against erosion, waves, flooding, and storm surge.[81]

Natural and nature-based infrastructure provides alternatives to traditional hard structure approaches such as seawalls, levees, and dikes and can improve the resilience of coastal communities and the integrity of coastal ecosystems.[81,82,83] This approach includes a range of efforts, such as the protection or restoration of natural habitats to mitigate waves and erosion (Figure 8.4) (see also Ch 19: Southeast, KM 3)[84,85,86,87,88,89] and hybrid approaches that combine built and natural features, such as some living shorelines options.[83,90] These types of approaches are being considered in the Superstorm Sandy Rebuild by Design challenge, the Changing Course competition

focused on the Lower Mississippi River delta, and in experimental studies and the development of guidance conducted within estuaries.[91] Studies suggest that healthy coastal ecosystems provide important cost savings in terms of flood damages avoided,[92,93,94] but more research would be useful to increase the level of confidence.

Natural and Nature-Based Infrastructure Habitats

Figure 8.4: Natural and nature-based infrastructure habitats include seagrass meadows (not shown), (a) coastal wetlands, (b) barrier islands, (c) beaches, (d) corals, (e) oyster reefs, and (f) dunes. Each of these habitats provides storm and erosion risk reduction by causing waves to break or slow as they roll over the ecosystem. Waves slow down, for example, as they flow across the rough surfaces and crests of reef ecosystems; likewise, water decelerates as it pushes through the vegetation of wetland ecosystems. This slowing decreases wave height and energy as the wave proceeds through or across each ecosystem, reducing the amount of erosion that the wave would otherwise cause. Photo credits: (a) Gretchen L. Grammer, NOAA National Ocean Service; (b) Erik Zobrist, NOAA Restoration Center; (c) NOAA; (d) LCDR Eric Johnson, NOAA Corps.; (e) Jonathan Wilker, Purdue University; (f) Ann Tihansky, USGS.

Key Message 3

Social Challenges Intensified

As the pace and extent of coastal flooding and erosion accelerate, climate change impacts along our coasts are exacerbating preexisting social inequities, as communities face difficult questions about determining who will pay for current impacts and future adaptation and mitigation strategies and if, how, or when to relocate. In response to actual or projected climate change losses and damages, coastal communities will be among the first in the Nation to test existing climate-relevant legal frameworks and policies against these impacts and, thus, will establish precedents that will affect both coastal and non-coastal regions.

Flooding and erosion impact many populations along the coast. However, for socially and economically marginalized and low-income groups, climate change and current and future SLR could exacerbate many long-standing inequities that precede any climate-related impacts (Figure 8.5) (see also Ch. 11: Urban, KM 1; Ch. 18: Northeast, KM 3).[95,96] Underrepresented and underserved communities facing additional threats from climate change span a variety of regions and contexts, ranging from the elderly in Florida[97] to rural and subsistence-based fishing communities in Alaska (Ch. 26: Alaska, KM 4).[98] The 2017 hurricane season provided grim imagery of the impacts to these socially and economically vulnerable coastal residents, and the long-term impacts on these communities are as yet unclear (Figure 8.6) (see also Ch. 2: Climate, Box 2.5). Given limited resources, the core of this challenge rests on questions about who is most vulnerable to the impacts, who should pay for losses incurred,

Societal Options for Resource Allocation in a Changing Climate

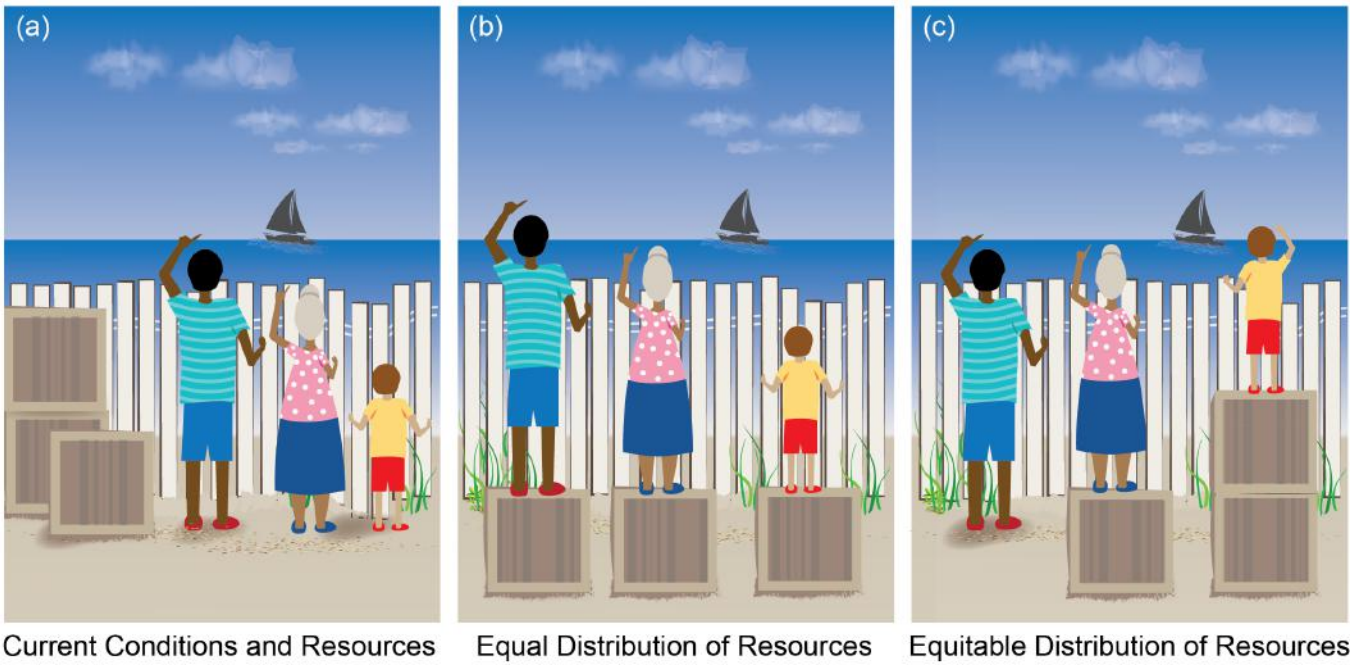

Figure 8.5: Society has limited resources to help individuals and communities adapt to climate change. Panel (a) illustrates that there are finite resources available and that individuals and communities are starting from different levels of readiness to adapt. Panel (b) illustrates the option for society to choose an equal allocation of resources where everyone gets the same amount of help, or as illustrated in panel (c), society can choose to distribute resources equitably to give people what they need to reach the same level of adaptation. Source: adapted with permission from Craig Froehle.

who should pay for protecting coastal communities in the future, and how governments and communities set protocols and policies for keeping people safe. These types of questions bring to light the divergent views of various stakeholders regarding the role of individuals, businesses, and governments in assuming the risks and benefits of living and working near the coast (Ch. 14: Human Health, KM 2 and 3).[99]

Adaptation strategies, including the decision to retreat from, accommodate, or protect against a particular impact, are dependent on several factors. Economically, a property owner's access to capital or insurance to fund these strategies contributes to adaptation choices, making poverty a driver of vulnerability in the face of climate-based impacts.[100] Some property owners can afford to modify their homes to withstand current and projected flooding and erosion impacts. Others who cannot afford to do so are becoming financially tied to houses that are at greater risk of annual flooding.[67] Additionally, communities are composed of renters and other individuals who do not own property, making it more difficult for them to contribute their voices to conversations about preserving neighborhoods. Culturally, coastal communities have ties to their specific land and to each other, as is the case from the bayous of Louisiana, to the beaches of New Jersey, to the sea islands of South Carolina and Georgia. These ties can impede people's ability and willingness to move away from impacted areas. For Indigenous villages to most effectively respond to critical climate impacts, decision-makers should consider identifying a suitable place to relocate that does not infringe on the needs and territories of other populations, is large enough for the entirety of the village, and is suitable for building and accessing infrastructure (Ch. 15: Tribes, KM 3).[101]

Impacts of the 2017 Hurricane Season

Figure 8.6: Quintana Perez dumps water from a cooler into floodwaters in the aftermath of Hurricane Irma in Immokalee, Florida. Photo credit: AP Photo/Gerald Herbert.

Climate change impacts are expected to drive human migration from coastal locations, but exactly how remains uncertain.[102,103,104] As demonstrated by the migration of affected individuals in the wake of Hurricane Katrina, impacts from storms can disperse refugees from coastal areas to all 50 states, with economic and social costs felt across the country.[105] Sea level rise might reshape the U.S. population distribution, with 13.1 million people potentially at risk of needing to migrate due to a SLR of 6 feet (about 2 feet less than the Extreme scenario) by the year 2100.[102] The Biloxi-Chitimacha-Choctaw tribe on Isle de Jean Charles in Louisiana was awarded $48 million from the U.S. Department of Housing and Urban Development to implement a resettlement plan.[106,107] The tribe is one of the few communities to qualify for federal funding to move en masse. (Ch. 15: Tribes, KM 3; Ch. 19: Southeast, KM 1).

Coastal Adaptation

Coasts will confront a more diverse and, to a great extent, unique range of climate stressors and impacts compared with the rest of the country. Rising sea levels will force many more coastal communities to grapple with chronic high tide flooding, higher storm surges, and associated emergency response costs over the next few decades.[6,7,36,75] The growing concentration of people and economic activity in coastal areas will introduce a greater degree of risk, including impacts that will ripple far beyond coastal communities themselves.[70,108]

Understanding these realities, coastal cities such as Boston, New York City, Miami, San Francisco, New Orleans, and Los Angeles are beginning to make investments to adapt to SLR (see the Case Study: "Key Messages in Action") (see also Ch. 19: Southeast, KM 1). From these efforts, and others like them, examples of successful adaptation planning are being collected to provide guidance to other communities facing similar challenges (Figure 8.2) (see also Ch. 28: Adaptation).[109,110,111]

However, while many current plans call for risk identification, monitoring, research, and additional planning, there is still little focus on the major investments or immediate implementation actions and cost-dependent tradeoffs required to successfully adapt.[110] The financial resources currently being devoted to adapt to or mitigate coastal climate change impacts are insufficient to meet the projected challenges ahead.[112,113,114] Additionally, with the limited and often expensive adaptation opportunities currently under consideration, including elevating properties or constructing seawalls, climate-driven impacts may lead to a great deal of unplanned and undesired community change that is likely to disproportionately impact communities that are already marginalized. Resilience planning that considers cultural heritage and incorporates community-driven values, experiences, concerns, needs, and traditional knowledge promotes social inclusivity and equity in adaptation decisions (Ch. 15: Tribes, KM 3).[115,116]

Case Study: Key Messages in Action—Norfolk, Virginia

Low-lying Norfolk—Virginia's second-largest city—is enduring serious physical, financial, and social impacts as the frequency of high tide flooding accelerates due to rising local sea level.[6] High tide flooding threatens access routes, historical neighborhoods, personal and commercial property integrity and value, and national security, given that Norfolk houses the world's largest naval base. The city has begun to invest in mitigation and adaptation actions,[117] but recent estimates indicate it will cost hundreds of millions of dollars to improve storm water pipes, flood walls, tide gates, and pumping stations.[118] Natural and nature-based infrastructure projects such as the Colley Bay living shoreline have improved water quality, mitigated erosion, and restored habitats.[119] Additional planned projects include constructing berms, reclaiming filled waterways and wetlands, and raising roads and structures. City officials have identified the neighborhoods of The Hague and Pretty Lake as top priorities for flood mitigation, but in other areas of the city where containment will be more difficult, residents face the possibility of abandoning their homes (Figure 8.7).[118,120]

Vision 2100: Designing the Coastal Community of the Future

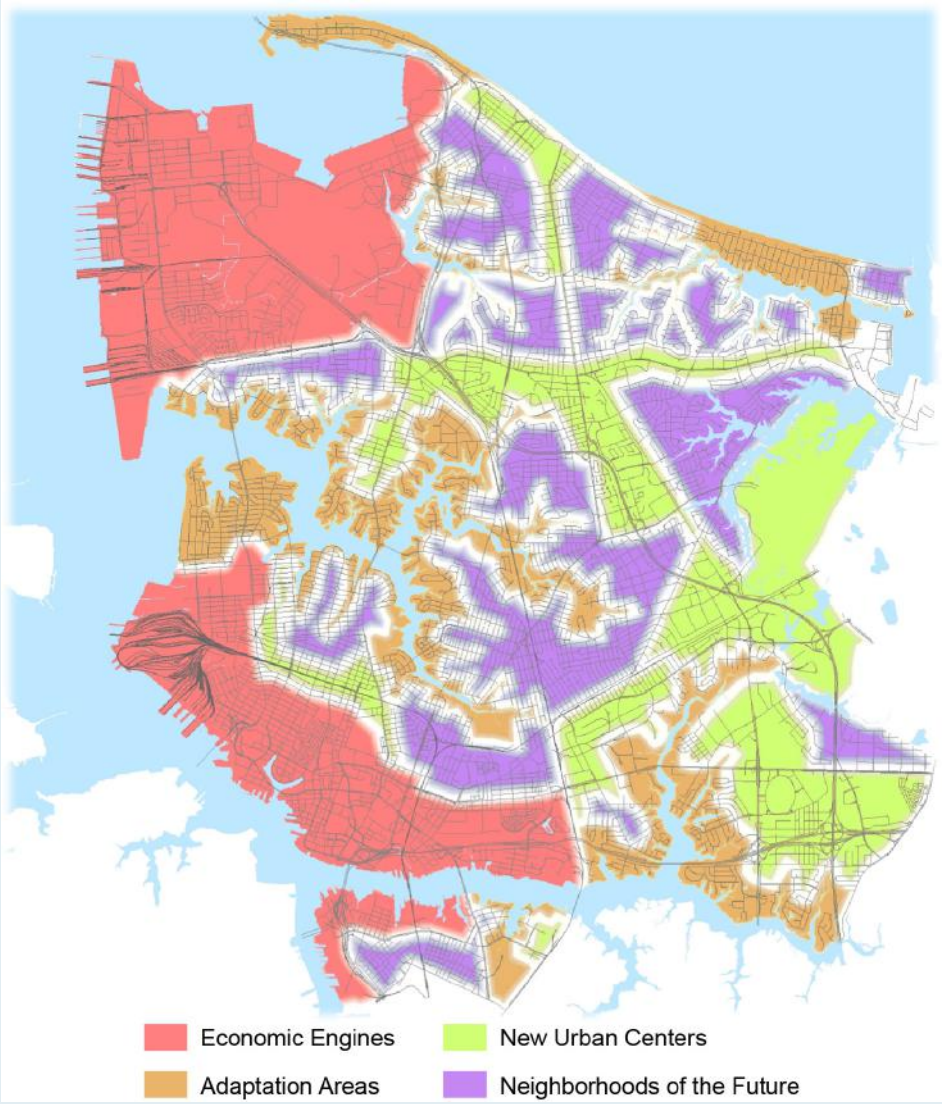

Figure 8.7: The City of Norfolk is building a long-term strategy to address the flooding challenges due to sea level rise. Green areas are at low risk of coastal flooding and have great potential for high-density, mixed-use, and mixed-income development. Red areas are home to key economic assets that are essential to the city's future. Brown areas are established neighborhoods that experience more frequent flooding. Purple areas are established neighborhoods at less risk of coastal flooding. (Descriptions in the legend are from the original City of Norfolk publication.) Source: City of Norfolk 2016.[120]

Case Study: Key Messages in Action—Norfolk, Virginia, *continued*

Recognizing these urgent and compelling needs, the Hampton Roads Adaptation Forum convened in 2012 to exchange knowledge and make recommendations to local government officials. Norfolk has become a member of the Rockefeller Foundation's 100 Resilient Cities, installed a chief resilience officer, and released a codified resilience strategy that outlines goals and metrics for the city.[121]

Given that the city is home to Naval Station Norfolk and other national security facilities, the Department of Defense has also contributed to plans for the city's future (Ch. 1: Overview, Figure 1.8). Naval Station Norfolk supports multiple aircraft carrier groups and is the duty station for thousands of employees.[122] Most of the area around the base lies less than 10 feet above sea level,[123] and local relative sea level is projected to rise between about 2.5 and 11.5 feet by the year 2100 under the Intermediate-Low global SLR scenario (considered likely under the lower [RCP4.5] and very low [RCP2.6] scenarios) and the Extreme SLR scenario (considered worst case under a higher scenario, RCP8.5), respectively.[36] The Navy is studying how flooding in Norfolk and Virginia Beach affects military readiness when sailors and other employees who live off-base are unable to reach the naval station for work.[124] Ultimately, the lessons learned in Norfolk—both the successes and challenges—are transferable to other coastal communities across the United States and its territories.

Acknowledgments

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Opening Image Credit

Natural "green barriers": NOAA.

Traceable Accounts

Process Description

The selection of the author team for the Coastal Effects chapter took into consideration the wide scope and relative sufficiency of the Third National Climate Assessment (NCA3) Coastal chapter. With input and guidance from the NCA4 Federal Steering Committee, the coordinating lead authors made the decision to convene an all-federal employee team with representation from key federal agencies with science, management, and policy expertise in climate-related coastal effects, and to focus the content of the chapter on Key Messages and themes that would both update the work conducted under NCA3 and introduce new themes. For additional information on the author team process and structure, refer to Appendix 1: Process.

A central component of the assessment process was a chapter lead authors' meeting held in Washington, DC, in May 2017. The Key Messages were initially developed at this meeting. Key vulnerabilities were operationally defined as those challenges that can fundamentally undermine the functioning of human and natural coastal systems. They arise when these systems are highly exposed and sensitive to climate change and (given present or potential future adaptive capacities) insufficiently prepared or able to respond. The vulnerabilities that the team decided to focus on were informed by a review of the existing literature and by ongoing interactions of the author team with coastal managers, planners, and stakeholders. In addition, the author team conducted a thorough review of the technical inputs and associated literature. Chapter development was supported by numerous chapter author technical discussions via teleconference from April to September 2017.

Key Message 1

Coastal Economies and Property Are Already at Risk

America's trillion-dollar coastal property market and public infrastructure are threatened by the ongoing increase in the frequency, depth, and extent of tidal flooding due to sea level rise, with cascading impacts to the larger economy. Higher storm surges due to sea level rise and the increased probability of heavy precipitation events exacerbate the risk. Under a higher scenario (RCP8.5), many coastal communities will be transformed by the latter part of this century, and even under lower scenarios (RCP4.5 or RCP2.6), many individuals and communities will suffer financial impacts as chronic high tide flooding leads to higher costs and lower property values. Actions to plan for and adapt to more frequent, widespread, and severe coastal flooding would decrease direct losses and cascading economic impacts. (*Likely, High Confidence*)

Description of evidence base

Significant impacts to coastal communities, properties, infrastructure, and services are already occurring in low-lying areas of the country such as Miami Beach and Fort Lauderdale in Florida; Norfolk, Virginia; and Charleston, South Carolina.[61,125,126,127,128]

Satellite and tide gauge data show that sea level rise (SLR) rates are increasing,[36] and research has shown that this increase is driven by emissions that are warming the planet.[129,130] The latest SLR science[7,36,48,52] finds that even if RCP2.6 were achieved, it is *likely* that global mean sea level will rise by 1.5 feet by 2100; under RCP8.5, a rise of about 3 feet is within the *likely* range for 2100.

Recent probabilistic studies and assessments of future SLR and rapid ice loss from Antarctica find that although a low probability, there is a possibility of upwards of 8 feet of rise by 2100 under a high-emission, extreme melt scenario.[36,37,49,50,51,52]

Applying digital elevation models to determine the extent and number of communities and the amount of property and infrastructure that would be impacted by different amounts of SLR illustrates the magnitude of investments that are at risk.[56,57,126,131,132,133,134] These same analyses demonstrate the savings that could be achieved by lowering emissions. Finally, implementing adaptation measures to ensure that public infrastructure is resilient to current and future flood scenarios will be tremendously expensive. To date there are few economic sectoral models that quantify damages under alternative climate scenarios,[57,134] so additional modeling work would be useful.

The importance of coastal economies and infrastructure to the overall national economy is well documented (for example, the National Oceanic and Atmospheric Administration's [NOAA] Economics: National Ocean Watch; NOAA port data), as are the economic ripple effects of impacts to property markets.[57,58,133,135,136] Similarly, much has been written about how the National Flood Insurance Program has subsidized development in risky areas and how raising flood insurance rates to be actuarially sound could make it impossible for many coastal residents to afford flood insurance.[58,137,138,139,140] The evidence for the economic savings provided by adaptation investments is still fairly limited but growing.[54,57,59,141]

Major uncertainties

The main source of uncertainty is in the magnitude of SLR that will occur and how it will vary across different regions, which depend in part on the amount and speed with which global society will reduce emissions. While global climate models and SLR models have improved since NCA3,[142] uncertainty remains about exactly how much SLR will occur where and by when with different emissions levels. Even though there is uncertainty about the magnitude, the probabilistic approach to the SLR technical report to the Fourth National Climate Assessment,[36] together with impacts already documented around the country from high tide flooding,[143] gives us *high confidence* of the threat to coastal property and infrastructure. Adaptive responses to SLR risk and impacts, including individual action and public policy development, are also significant sources of uncertainty. For example, there is uncertainty about future development patterns in coastal regions, including both new development and migration inland, which has the potential to change the magnitude of coastal property and infrastructure at risk. The U.S.-specific research on potential migration away from the coast due to SLR and other climate impacts is very limited.[102]

Future flood insurance policy is another specific source of uncertainty. Under the latest legislation (the Federal Emergency Management Agency's Homeowner Flood Insurance Affordability Act, 2017[140]), flood insurance rates are gradually rising; development of new policies related to affordability or to the requirement to carry flood insurance in order to have a federally backed mortgage could change behaviors.

While figures for the economic value of certain sectors dependent on the ocean and Great Lakes are available through NOAA's "Economics: National Ocean Watch,"[144] similar information for the economic and social value of other sectors, such as real estate and insurance/reinsurance, would be beneficial for the audience of this assessment report, especially decision-makers.

Description of confidence and likelihood

There is *very high confidence* that the frequency and extent of tidal flooding is already increasing and will continue to increase with SLR and that this flooding threatens the trillion-dollar coastal property market and public infrastructure. There is limited research using varied methods to quantify the direct and indirect economic impacts that will be experienced under different amounts of SLR. Nevertheless, there is a *high level of confidence* that these losses will be dramatic under SLR associated with the higher emission scenario (RCP8.5) and significant even under lower scenarios (RCP4.5 or RCP2.6), based on property values and geographic exposure to inundation. U.S. economic history provides strong evidence that extensive property market losses have the potential to impact businesses, personal wealth, and mortgage-related securities. Similarly, historic disaster events such as hurricanes and earthquakes provide a *very high level of confidence* that impacts to critical transportation and energy networks will harm the economy. Considering the uncertainty inherent in future human behavior and policy responses, including flood insurance policy, it is possible that individuals and institutions will act to reduce future flooding, to lessen the exposure and sensitivity of critical assets, and to create policies that assist individuals and businesses most impacted; hence, there is *medium confidence* that many coastal communities will be transformed by 2100 under any scenario and that many individuals will be financially devastated under lower emission scenarios (RCP4.5 or RCP2.6). Considering current exposure of assets and the latest SLR science, large economic losses in coastal regions that will generate cascading impacts to the overall economy of the United States are considered to be *likely*. The overall *high confidence* is the net result of considering the evidence base, the well-established accumulation of economic assets and activities in coastal areas, and the directional trend of sea level rise.

Key Message 2

Coastal Environments Are at Already at Risk

Fisheries, tourism, human health, and public safety depend on healthy coastal ecosystems that are being transformed, degraded, or lost due in part to climate change impacts, particularly sea level rise and higher numbers of extreme weather events (*highly likely, high confidence*). Restoring and conserving coastal ecosystems and adopting natural and nature-based infrastructure solutions can enhance community and ecosystem resilience to climate change, help to ensure their health and vitality, and decrease both direct and indirect impacts of climate change (*likely, high confidence*).

Description of evidence base

Multiple lines of evidence have determined that coastal environments are critical to support coastal fisheries, tourism, and human health and safety.[74,81,83,85,86,87,92,145,146,147] These ecosystems are some of the most threatened on the planet and are being transformed, degraded, or destroyed due to climate change (including rising temperatures, rising sea levels, and ocean acidification)[148,149,150,151,152,153] and due to other human stressors such as nutrient pollution, habitat and biodiversity loss, and overfishing.

There is growing evidence that one part of the solution to help coastal ecosystems and human communities be more resilient to climate change, including SLR and increasingly intense or

frequent storms, is to conserve or restore coastal habitats such as wetlands, beaches and dunes, oyster and coral reefs, and mangroves[74,75,81,83,85,86,87,88,92,145,146,154] because they help to attenuate waves, decrease wave energy, and reduce erosion.[81] In addition to restoring or protecting natural habitats, there is also a growing interest in, and body of research regarding expectations for, performance in using a combination of natural and built (called hybrid, or nature-based) features, such as living shorelines, to protect coastal communities.[83,88,90,91,155,156]

Major uncertainties

The exact amount of coastal habitat loss that is due to climate change versus other human stressors or multiple stressors can be hard to ascertain, because these stressors are all acting simultaneously on coastal habitats. Nevertheless, it is clear that climate change is one of the important stressors impacting coastal habitats and leading to the degradation or loss of these ecosystems, such as the loss of coral habitats to bleaching events due to rising ocean temperatures and the loss of coastal wetlands due to more intense storm events.

The use of natural and nature-based infrastructure (NNBI) to improve coastal resilience is being implemented in many different states (for example, the use of living shorelines is expanding in Maryland, North Carolina, New Jersey, Louisiana, and other states, and the Rebuild by Design competition is implementing a variety of coastal resilience projects in New York and New Jersey), although there remain some uncertainties about how much storm and erosion risk reduction is provided by different techniques or projects and in different settings. The efficacy of NNBI remains uncertain in many instances; comprehensive monitoring, particularly during and after storms, would be required to ascertain how well these features are functioning for protection services. This monitoring could inform future coastal resilience planning and decisions, including the benefits, costs, and/or tradeoffs involved in considering NNBI options.[157]

Description of confidence and likelihood

There is *high confidence* that coastal ecosystems are particularly vulnerable to climate change. They have already been dramatically altered by human stressors, as documented in extensive and conclusive evidence; additional stresses from climate change point to a growing likelihood of coastal ecosystems being pushed past tipping points from which they will not be able to recover. The overall *high confidence* is the net result of considering the evidence base, the dramatically altered ecosystems from human stresses, and the directional trend of sea level rise.

Key Message 3

Social Challenges Intensified

As the pace and extent of coastal flooding and erosion accelerate, climate change impacts along our coasts are exacerbating preexisting social inequities, as communities face difficult questions about determining who will pay for current impacts and future adaptation and mitigation strategies and if, how, or when to relocate. In response to actual or projected climate change losses and damages, coastal communities will be among the first in the Nation to test existing climate-relevant legal frameworks and policies against these impacts and, thus, will establish precedents that will affect both coastal and non-coastal regions. (*Likely*, *Very High Confidence*)

Description of evidence base

Reports and peer-reviewed articles are clear that socioeconomic challenges are being both driven and intensified by climate change.[33] Particularly on the coasts, where there are multiple risks to contend with, including hurricanes, SLR, shoreline erosion, and flooding, the high cost of adaptation is proving to be beyond the means of some communities and groups.[97,100,158] In areas where relocation is more feasible than in-place adaptation, coastal tribes of Indigenous people are at risk of losing their homes, cultures, and ways of life as they seek higher ground (Ch. 15: Tribes, KM 3).[98,159] New tools are being developed to quantify risks and vulnerabilities along the coast. For example, tools such as the Coastal Community Social Vulnerability Index[160] and the Coastal Economic Vulnerability Index[161] measure the social vulnerability of hurricane- or flood-prone areas to better quantify and predict how climate-driven changes are likely to impact marginalized groups. The Coastal Flood Exposure Mapper tool[162] supports communities that are assessing their coastal hazard risks and vulnerabilities with user-defined maps that show the people, places, and natural resources exposed to coastal flooding. The U.S. Environmental Protection Agency's Environmental Justice Screening and Mapping Tool provides consistent national data that allows the agency to protect the public health and environments of all populations, with a focus on traditionally underserved communities.[163] Moreover, involving diverse representation in the adaptation process through community-driven resilience planning[115] is likely to be a part of developing adaptation strategies that are fair and just.[99,164]

Major uncertainties

The main uncertainty for this Key Message is predicated on how different types of coastal effects (chronic flooding versus storms) will impact areas and communities along the coast. The degree of variation between communities means that it will be challenging to predict exactly which communities will be affected and to what extent, but the evidence thus far is clear: when it comes to climate-driven challenges and adaptation strategies, areas that have traditionally been underrepresented will continue to suffer more than wealthier or more prominent areas. Large-scale infrastructure investments are made in some areas and not others, and some local governments will not be able to afford what they need to do.

The variability in state laws and the pace at which those laws are evolving (such as shoreline management plans and setback policies for structures in the coastal zone) create major uncertainty.

Description of confidence and likelihood

There is *very high confidence* that structural inequalities in coastal communities will be exacerbated by climate change and its attendant effects (for example, storms, erosion). In the absence of clear policies and legal precedent, questions about land ownership and home ownership will persist.

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9 Oceans and Marine Resources

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9 Oceans and Marine Resources

Coral reefs in the U.S. Virgin Islands

Key Message 1

Ocean Ecosystems

The Nation's valuable ocean ecosystems are being disrupted by increasing global temperatures through the loss of iconic and highly valued habitats and changes in species composition and food web structure. Ecosystem disruption will intensify as ocean warming, acidification, deoxygenation, and other aspects of climate change increase. In the absence of significant reductions in carbon emissions, transformative impacts on ocean ecosystems cannot be avoided.

Key Message 2

Marine Fisheries

Marine fisheries and fishing communities are at high risk from climate-driven changes in the distribution, timing, and productivity of fishery-related species. Ocean warming, acidification, and deoxygenation are projected to increase these changes in fishery-related species, reduce catches in some areas, and challenge effective management of marine fisheries and protected species. Fisheries management that incorporates climate knowledge can help reduce impacts, promote resilience, and increase the value of marine resources in the face of changing ocean conditions.

Key Message 3

Extreme Events

Marine ecosystems and the coastal communities that depend on them are at risk of significant impacts from extreme events with combinations of very high temperatures, very low oxygen levels, or very acidified conditions. These unusual events are projected to become more common and more severe in the future, and they expose vulnerabilities that can motivate change, including technological innovations to detect, forecast, and mitigate adverse conditions.

Executive Summary

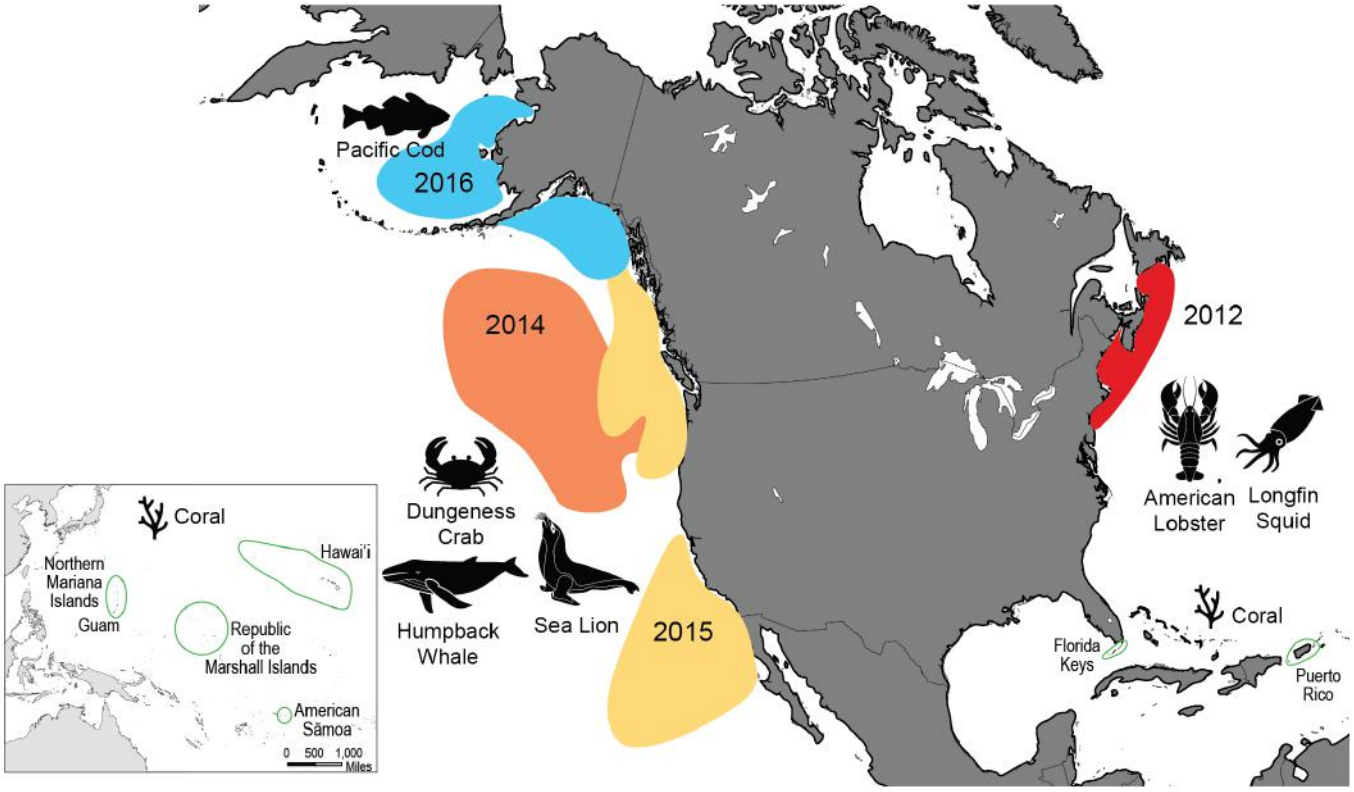
Americans rely on ocean ecosystems for food, jobs, recreation, energy, and other vital services. Increased atmospheric carbon dioxide levels change ocean conditions through three main factors: warming seas, ocean acidification, and deoxygenation. These factors are transforming ocean ecosystems, and these transformations are already impacting the U.S. economy and coastal communities, cultures, and businesses.

While climate-driven ecosystem changes are pervasive in the ocean, the most apparent impacts are occurring in tropical and polar ecosystems, where ocean warming is causing the loss of two vulnerable habitats: coral reef and sea ice ecosystems. The extent of sea ice in the Arctic is decreasing, which represents a direct loss of important habitat for animals like polar bears and ringed seals that use it for hunting, shelter, migration, and reproduction, causing their abundances to decline (Ch. 26: Alaska, KM 1). Warming has led to mass bleaching and/or outbreaks of coral diseases off the coastlines of Puerto Rico, the U.S. Virgin Islands, Florida, Hawai'i, and the U.S.-Affiliated Pacific Islands (Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawai'i & Pacific Islands, KM 4) that threaten reef ecosystems and the people who depend on them. The loss of the recreational benefits alone from coral reefs in the United States is expected to reach $140 billion (discounted at 3% in 2015 dollars) by 2100. Reducing greenhouse gas emissions (for example, under RCP4.5) (see the Scenario Products section of App. 3 for more on scenarios) could reduce these cumulative losses by as much as $5.4 billion but will not avoid many ecological and economic impacts.

Ocean warming, acidification, and deoxygenation are leading to changes in productivity, recruitment, survivorship, and, in some cases, active movements of species to track their preferred temperature conditions, with most moving northward or into deeper water with warming oceans. These changes are impacting the distribution and availability of many commercially and recreationally valuable fish and invertebrates. The effects of ocean warming, acidification, and deoxygenation on marine species will interact with fishery management decisions, from seasonal and spatial closures to annual quota setting, allocations, and fish stock rebuilding plans. Accounting for these factors is the cornerstone of climate-ready fishery management. Even without directly accounting for climate effects, precautionary fishery management and better incentives can increase economic benefits and improve resilience.

Short-term changes in weather or ocean circulation can combine with long-term climate trends to produce periods of very unusual ocean conditions that can have significant impacts on coastal communities. Two such events have been particularly well documented: the 2012 marine heat wave in the northwestern Atlantic Ocean and the sequence of warm ocean events between 2014 and 2016 in the northeastern Pacific Ocean, including a large, persistent area of very warm water referred to as the Blob. Ecosystems within these regions experienced very warm conditions (more than 3.6°F [2°C] above the normal range) that persisted for several months or more. Extreme events in the oceans other than those related to temperature, including ocean acidification and low-oxygen events, can lead to significant disruptions to ecosystems and people, but they can also motivate preparedness and adaptation.

Extreme Events in U.S. Waters Since 2012



The 2012 North Atlantic heat wave was concentrated in the Gulf of Maine; however, shorter periods with very warm temperatures extended from Cape Hatteras to Iceland during the summer of 2012. American lobster and longfin squid and their associated fisheries were impacted by the event.[1] The North Pacific event began in 2014[2] and extended toward the shore in 2015[3,4] and into the Gulf of Alaska in 2016,[5,6] leading to a large bloom of toxic algae that impacted the Dungeness crab fishery and contributed directly and indirectly to deaths of sea lions and humpback whales. U.S. coral reefs that experienced moderate to severe bleaching during the 2015–2016 global mass bleaching event[7] are indicated by coral icons. *From Figure 9.3 (Source: Gulf of Maine Research Institute).*

State of the Ocean

From tropical waters in Hawai'i and Florida, to temperate waters in New England and the Pacific Northwest, to cold Arctic seas off of Alaska, the United States has some of the most diverse and productive ocean ecosystems in the world. Americans rely on ocean ecosystems for food, jobs, recreation, energy, and other vital services, and coastal counties of the United States are home to over 123 million people, or 39% of the U.S. population (Ch. 8: Coastal).[8] The fishing sector alone contributes more than $200 billion in economic activity each year and supports 1.6 million jobs.[9] Coastal ecosystems like coral and oyster reefs, kelp forests, mangroves, and salt marshes provide habitat for many species and shoreline protection from storms, and they have the capacity to sequester carbon.[10,11,12,13]

The oceans play a pivotal role in the global climate system by absorbing and redistributing both heat and carbon dioxide.[14,15] Since the Third National Climate Assessment (NCA3),[16] understanding of the physical, chemical, and biological conditions in the oceans has increased, allowing for improved detection, attribution, and projection of the influence of human-caused carbon emissions on oceans and marine resources.

Human-caused carbon emissions influence ocean ecosystems through three main processes: ocean warming, acidification, and deoxygenation. Warming is the most obvious and well-documented impact of climate change on the ocean. Ocean surface waters have warmed on average 1.3° ± 0.1°F (0.7° ± 0.08°C) per century globally between 1900 and 2016, and more than 90% of the extra heat linked to carbon emissions is contained in the ocean.[15] This warming impacts sea levels, ocean circulation, stratification (density contrast between the surface and deeper waters), productivity, and, ultimately, entire ecosystems. Changes in temperature in the ocean and in the atmosphere alter ocean currents and wind patterns, which influence the seasonality, abundance, and diversity of phytoplankton and zooplankton communities that support ocean food webs.[17,18]

In addition to warming, excess carbon dioxide (CO_2) in the atmosphere has a direct and independent effect on the chemistry of the ocean. When CO_2 dissolves in seawater, it changes three aspects of ocean chemistry.[15,19,20,21] First, it increases dissolved CO_2 and bicarbonate ions, which are used by algae and plants as the fuel for photosynthesis, potentially benefiting many of these species. Second, it increases the concentration of hydrogen ions, acidifying the water. Acidity is measured with the pH scale, with lower values indicating more acidic conditions. Third, it reduces the concentration of carbonate ions. Carbonate is a critical component of calcium carbonate, which is used by many marine organisms to form their shells or skeletons. The saturation state of calcium carbonate is expressed as the term Ω. When the concentration of carbonate ions in ocean water is low enough to yield $\Omega < 1$ (referred to as undersaturated conditions), exposed calcium carbonate structures begin to dissolve. For simplicity, the terms ocean acidification and acidifying will refer to the suite of chemical changes discussed above.

Increased CO_2 levels in the atmosphere are also causing a decline in ocean oxygen concentrations.[15] Deoxygenation is linked to ocean warming through the direct influence of temperature on oxygen solubility (warm water holds less oxygen). Warming of the ocean surface creates an enhanced vertical density contrast, which reduces the transfer of oxygen below the surface. Ecosystem changes related

to temperature and stratification further influence oxygen dynamics by altering photosynthesis and respiration.[22,23]

All three of these processes—warming, acidification, and deoxygenation—interact with one another and with other stressors in the ocean environment. For example, nitrogen fertilizer running off the land and entering the Gulf of Mexico through the Mississippi River stimulates algal blooms that eventually decay, creating a large dead zone of water with very low oxygen[24,25] and, simultaneously, low pH.[26] Warmer conditions at the surface slow down the rate at which oxygen is replenished, magnifying the impact of the dead zone. Changes in temperature in the ocean and in the atmosphere affect ocean currents and wind patterns that can alter the dynamics of phytoplankton blooms,[17] which then drive low-oxygen and low-pH events in coastal waters.

Transformations in ocean ecosystems are already impacting the U.S. economy and the coastal communities, cultures, and businesses that depend on ocean ecosystems (Key Message 1). Fisheries provide the most tangible economic benefit of the ocean. While the impact of warming on fish stocks is becoming more severe, there has also been progress in adapting fisheries management to a changing climate (Key Message 2). Finally, the ability for climate-related changes in ocean conditions to impact the United States was made especially clear by major marine heat wave events that occurred along the Northeast Coast in 2012 and along the entire West Coast in 2014–2016 (Key Message 3). During these events, the regions experienced high ocean temperatures similar to the average conditions expected later this century under future climate scenarios. Ecosystem changes included the appearance of warm-water species, increased mortality of marine mammals, and an unprecedented harmful algal bloom, and these factors combined to produce economic stress in some of the Nation's most valuable fisheries.

Key Message 1

Ocean Ecosystems

The Nation's valuable ocean ecosystems are being disrupted by increasing global temperatures through the loss of iconic and highly valued habitats and changes in species composition and food web structure. Ecosystem disruption will intensify as ocean warming, acidification, deoxygenation, and other aspects of climate change increase. In the absence of significant reductions in carbon emissions, transformative impacts on ocean ecosystems cannot be avoided.

Marine species are sensitive to the physical and chemical conditions of the ocean; thus, warming, acidification, deoxygenation, and other climate-related changes can directly affect their physiology and performance.[27,28,29] Differences in how species respond to physical conditions lead to changes in their relative abundance within an ecosystem as species decline or increase in abundance, colonize new locations, or leave places where conditions are no longer favorable.[30,31,32,33] Such reorganization of species in marine communities can result in some species losing resources they depend on for their survival (such as prey or shelter). Other species may be exposed to predators, competitors, and diseases they have rarely encountered before and to which they have not evolved behavioral responses or other defenses.[34,35,36] Climate change is creating communities that are ecologically different from those that currently exist in ocean ecosystems. Reorganization of these communities would change the ecosystem services provided by marine ecosystems in ways that influence regional economies, fisheries harvest,

aquaculture, cultural heritage, and shoreline protection (Figure 9.1) (see also Ch. 7: Ecosystems, KM 1; Ch. 8: Coastal, KM 2).[37,38,39,40]

While climate-driven ecosystem changes are pervasive, the most apparent impacts are occurring in tropical and polar ecosystems, where ocean warming is causing the loss of two vulnerable habitats: coral reef and sea ice ecosystems.[41,42] Warming is leading to an increase in coral bleaching events around the globe,[7] and mass bleaching and/or outbreaks of coral diseases have occurred off the coastlines of Puerto Rico, the U.S. Virgin Islands, Florida, Hawai'i, and the U.S.-Affiliated Pacific Islands.[43,44] Loss of reef-building corals alters the entire reef ecosystem, leading to changes in the communities of fish and invertebrates that inhabit reefs.[45,46] These changes directly impact coastal communities that depend on reefs for food, income, storm protection, and other services (Figure 9.1) (see also Ch. 27: Hawai'i & Pacific Islands, KM 4).

The extent of sea ice in the Arctic is decreasing, further exacerbating temperature changes and increasing corrosiveness in the Arctic Ocean (Ch. 26: Alaska, KM 1).[15] The decline in sea ice represents a direct loss of important habitat for animals like polar bears and ringed seals that use ice for hunting, shelter, migration, and reproduction, causing their abundances to decline.[47,48,49] The Arctic Ocean food web is fueled by intense blooms of algae that occur at the ice edge. Loss of sea ice is also shifting the location and timing of these blooms, impacting the food web up to fisheries and top predators like killer whales (Ch. 26: Alaska, Figure 26.4).[50,51,52] Surface waters around Alaska have or will soon become permanently undersaturated with respect to calcium carbonate, further stressing these ecosystems (Ch. 26: Alaska, Figure 26.3).

Projected Impacts

The majority of marine ecosystems in the United States and around the world now experience acidified conditions that are entirely different from conditions prior to the industrial revolution (Ch. 7: Ecosystems).[14,53,54] Models estimate that by 2050 under the higher emissions scenario (RCP8.5) (see the Scenario Products section of App. 3 for more on scenarios) most ecosystems (86%) will experience combinations of temperature and pH that have never before been experienced by modern species.[54] Regions of the ocean with low oxygen concentrations are expected to expand and to increasingly impinge on coastal ecosystems.[15,55,56] Warming and ocean acidification pose very high risks for many marine organisms, including seagrasses, warm water corals, pteropods, bivalves, and krill over the next 85 years.[57] Ocean acidification and hypoxia (low oxygen levels) that co-occur in coastal zones will likely pose a greater risk than if species were experiencing either independently.[58] Furthermore, under the higher scenario (RCP8.5), by the end of this century, nearly all coral reefs are projected to be surrounded by acidified seawater that will challenge coral growth.[59]

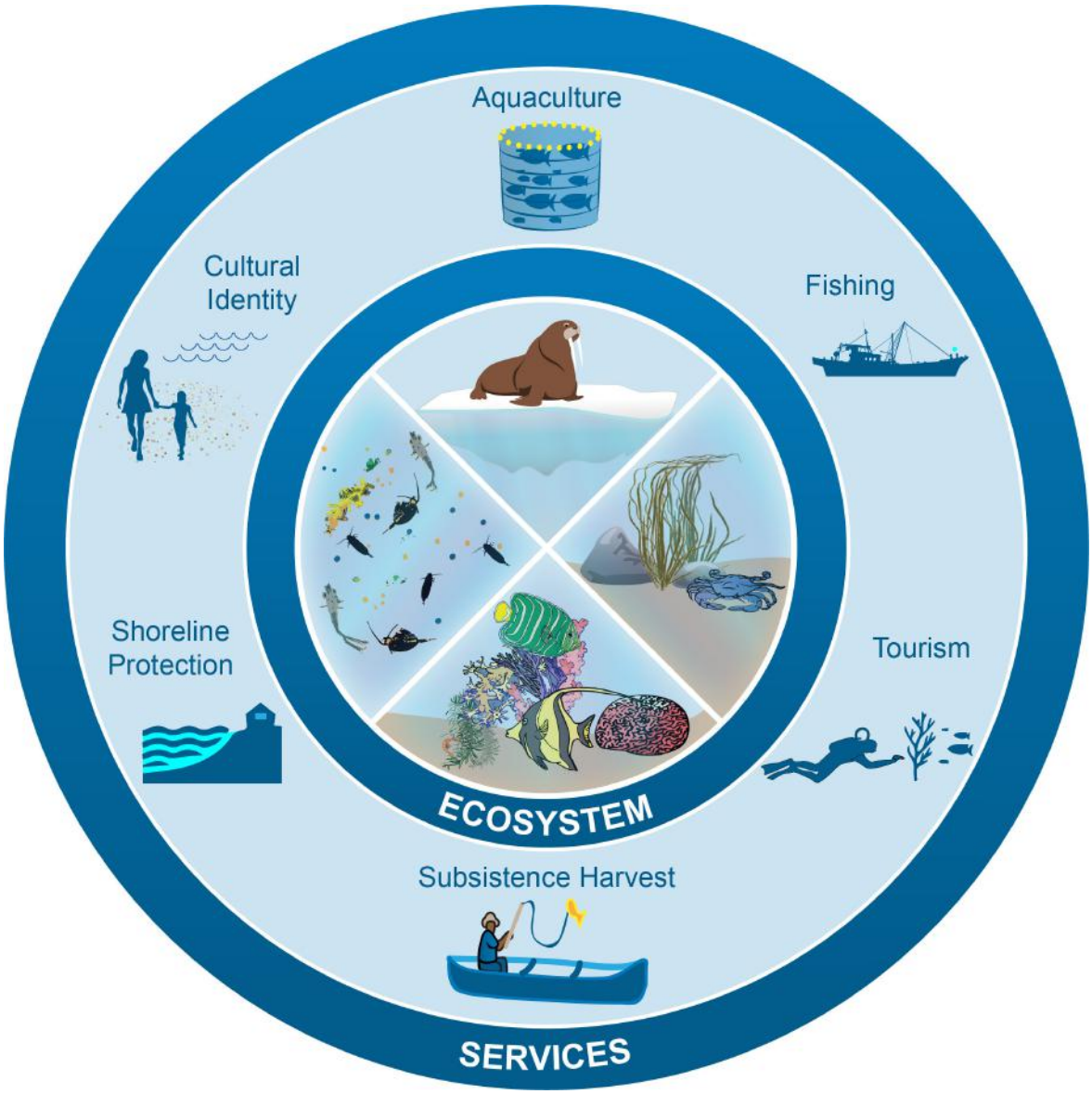


Figure 9.1: The diagram shows some marine ecosystems (center) and the services they provide to human communities (outer ring). Marine ecosystems in the United States range from tropical coral reefs (center bottom) to sea ice ecosystems in the Arctic (center top). They also include ecosystems with freely drifting plankton (center left) and with animals and seaweed that live on the ocean bottom (center right). Climate change is disrupting the structure and function of marine ecosystems in the United States and altering the services they provide to people. These services include food from fishing (commercial, recreational, and subsistence harvest) and aquaculture, economic benefits from tourism, protection of coastal property from storms, and nonmarket goods such as the cultural identity of coastal communities. Source: NOAA.

Changes in biodiversity in the ocean are underway, and over the next few decades will likely transform marine ecosystems.[33] The species diversity of temperate ecosystems is expected to increase as traditional collections of species are replaced by more diverse communities similar to those found in warmer water.[60] Diversity is expected to decline in the warmest ecosystems; for example, one study projects that nearly all existing species will be excluded from tropical reef communities by 2115 under the higher scenario (RCP8.5).[61]

Climate-induced disruption to ocean ecosystems is projected to lead to reductions in important ecosystem services, such as

aquaculture and fishery productivity (Key Message 2) and recreational opportunities (Figure 9.1) (Ch. 7: Ecosystems, KM 1). Eelgrass, saltmarsh, and coral reef ecosystems also help protect coastlines from coastal erosion by dissipating the energy in ocean waves (Ch. 8: Coastal, KM 2). The loss of the recreational benefits alone from coral reefs in the United States is expected to reach $140 billion by 2100 (discounted at 3% in 2015 dollars).[62] Reducing greenhouse gas emissions (for example, under RCP4.5) could reduce these cumulative losses by as much as $5.4 billion but will not avoid many ecological and economic impacts.[62]

Opportunities for Reducing Risk

Warming, acidification, and reduced oxygen conditions will interact with other non-climate-related stressors such as pollution or overfishing (Key Message 2). Conservation measures such as efforts to protect older individuals within species,[63,64] maintain healthy fish stocks (Key Message 2),[65] and establish marine protected areas can increase resilience to climate impacts.[66,67,68] However, these approaches are inherently limited, as they do not address the root cause of warming, acidification, or deoxygenation. There is growing evidence that many ecosystem changes can be avoided only with substantial reductions in the global average atmospheric CO_2 concentration.[57,69,70]

Emerging Issues and Research Gaps

Species can adapt or acclimatize to changing physical and chemical conditions, but little is known about species' adaptive capacity and whether the rate of adaptation is fast enough to keep up with the unprecedented rate of change to the environment.[71,72,73] Furthermore, ocean ecosystems are becoming increasingly novel, meaning that knowledge of current ecosystems will be a less reliable guide for future decision-making (Ch. 28: Adaptation, KM 2). Continued monitoring to measure the effects of warming, acidification, and deoxygenation on marine ecosystems, combined with laboratory and field experiments to understand the mechanisms of change, will enable improved projections of future change and identification of effective conservation strategies for changing ocean ecosystems.

Key Message 2

Marine Fisheries

Marine fisheries and fishing communities are at high risk from climate-driven changes in the distribution, timing, and productivity of fishery-related species. Ocean warming, acidification, and deoxygenation are projected to increase these changes in fishery-related species, reduce catches in some areas, and challenge effective management of marine fisheries and protected species. Fisheries management that incorporates climate knowledge can help reduce impacts, promote resilience, and increase the value of marine resources in the face of changing ocean conditions.

Variability in ocean conditions can have significant impacts on the distribution and productivity (growth, survival, and reproductive success) of fisheries species.[74,75] For stocks near the warm end of their range (such as cod in the Gulf of Maine),[76] increases in temperature generally lead to productivity declines; in contrast, warming can enhance the productivity of stocks at the cold end of their range (such as Atlantic croaker).[77] These changes in productivity have direct economic and social impacts. For example, warming water temperatures in the Gulf of Maine exacerbated overfishing of Gulf of Maine cod, and the subsequent low quotas have resulted in socioeconomic stress in New England.[76] Reductions in the abundance of Pacific cod associated with the recent heat wave in the Gulf of Alaska led to an inability of

the fishery to harvest the Pacific cod quota in 2016 and 2017, and to an approximately 80% reduction in the allowable quota in 2018.[78]

Changes in productivity, recruitment, survivorship, and, in some cases, active movements of target species to track their preferred temperature conditions are leading to shifts in the distribution of many commercially and recreationally valuable fish and invertebrates, with most moving poleward or into deeper water with warming oceans.[31,79,80,81,82] Shifts in fish stock distributions can have significant implications for fisheries management, fisheries, and fishing-dependent communities. Fishers may be expected to move with their target species; however, fishing costs, port locations, regulations, and other factors can constrain the ability of the fishing industry to closely track changes in the ocean.[83] Shifts across governance boundaries are already creating management challenges in some regions and can become trans-boundary issues for fish stocks near national borders (Ch. 16: International, KM 4).[84]

Changes in the timing of seasonal biological events can also impact the timing and location of fisheries activities. The timing of peak phytoplankton and zooplankton biomass is influenced by oceanographic conditions (such as stratification and temperature).[85,86] Since juvenile fish survival and growth are dependent on food availability, variability in the timing of plankton blooms affects fish productivity (e.g., Malick et al. 2015[87]). Migration and spawning, events that often depend on temperature conditions, are also changing.[1,88,89,90] For example, management of the Chesapeake Bay striped bass fishery is based on a fixed fishing season that is meant to avoid catching large egg-bearing females migrating early in the season. As temperatures rise, more females will spawn early in the season, reducing their availability to fishers.[89] The location and size of coastal hypoxic zones (which are likely exacerbated by temperature and ocean acidification)[56] can affect the spatial dynamics of fisheries, such as the Gulf of Mexico shrimp fishery, with potential economic repercussions.[91]

Projected Impacts

The productivity, distribution, and phenology of fisheries species will continue to change as oceans warm and acidify. These changes will challenge the ability of existing U.S. and international frameworks to effectively manage fisheries resources and will have a variety of impacts on fisheries and fishing-dependent sectors and communities. Projected increases in ocean temperature are expected to lead to declines in maximum catch potential under a higher scenario (RCP8.5) in all U.S. regions except Alaska (Figure 9.2).[92] Because tropical regions are already some of the warmest, there are few species available to replace species that move to cooler water.[61] This means that fishing communities in Hawai'i and the Pacific Islands, the Caribbean, and the Gulf of Mexico are particularly vulnerable to climate-driven changes in fish populations. Declines of 10%–47% in fish catch potential in these warm regions, as compared to the 1950–1969 level, are expected with a 6.3°F (3.5°C) increase in global atmospheric surface temperature relative to preindustrial levels (reached by 2085 under RCP8.5).[92] In contrast, total fish catch potential in the Gulf of Alaska is projected to increase by approximately 10%, while Bering Sea catch potential may increase by 46%.[92] However, species-specific work suggests that catches of Bering Sea pollock, one of the largest fisheries in the United States, are expected to decline,[93] although price increases may mitigate some of the economic impacts.[94] Similarly, abundance of the most valuable fishery in the United States, American lobster, is projected to decline under RCP8.5.[64] Ocean acidification is expected to reduce harvests of U.S. shellfish, such as the Atlantic sea scallop;[95] while future work will

better refine impacts, cumulative consumer losses of $230 million (in 2015 dollars) across all U.S. shellfish fisheries are anticipated by 2099 under the higher scenario (RCP8.5).[62]

The implications of the projected changes in fisheries dynamics on revenue[94,96] and small-scale Indigenous fisheries remain uncertain.[97] Indigenous peoples depend on salmon and other fishery resources for both food and cultural value, and reductions in these species would pose significant challenges to some communities (e.g., Krueger and Zimmerman 2009[98]) (Ch. 15: Tribes, KM 2; Ch. 24: Northwest). Additionally, western Alaska communities receive a significant share of the revenues generated by Alaska groundfish fisheries through the Western Alaska

Projected Changes in Maximum Fish Catch Potential

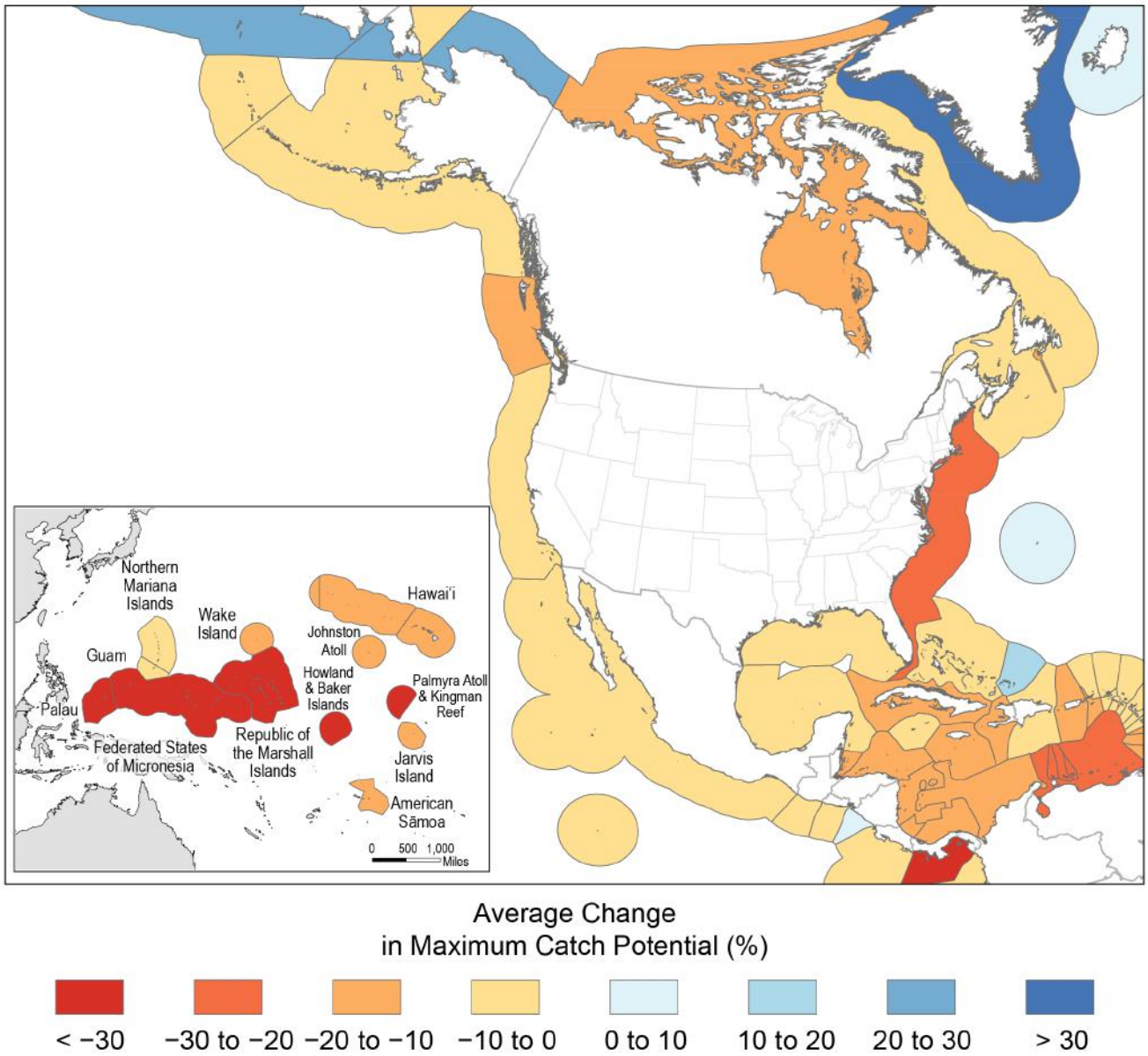


Figure 9.2: The figure shows average projected changes in fishery catches within large marine ecosystems for 2041–2060 relative to 1991–2010 under a higher scenario (RCP8.5). All U.S. large marine ecosystems, with the exception of the Alaska Arctic, are expected to see declining fishery catches. Source: adapted from Lam et al. 2016.[96]

Community Development Quota program.[99] This program provides an important source of fishery-derived income for these communities. Where there is strong reliance of fish stocks on specific habitats, shifts may lead to fish becoming more concentrated when water temperature or other changes in ocean conditions push species against a physical boundary such as ice or the ocean bottom.[83] Alternatively, shifts in species distributions are likely to drive vessels farther from port, increasing fishing costs and potentially impacting vessel safety.[100] Under such conditions, there will also be new opportunities that result from species becoming more abundant or spatially available. Advance knowledge and projections of anticipated changes allow seafood producers to develop new markets and harvesters the ability to adapt their gear and fishing behavior to take advantage of new opportunities.[84,101,102]

Opportunities for Reducing Risk

A substantial reduction of greenhouse gas emissions would reduce climate-driven ocean changes and significantly reduce risk to fisheries.[103] Warming, acidification, and deoxygenation interact with fishery management decisions, from seasonal and spatial closures to annual quota setting, allocations, and fish stock rebuilding plans. Accounting for these factors is the cornerstone of climate-ready fishery management.[84,104,105] Modeling studies show that climate-ready, ecosystem-based fisheries management can help reduce the impacts of some anticipated changes and increase resilience under changing conditions.[93,106,107] There is now a national strategy for integrating climate information into fishery decision-making,[105] and the North Pacific Fishery Management Council is now directly incorporating ocean conditions and climate projections in its planning and decision-making.[108,109]

National and regional efforts have been underway to characterize community vulnerability to climate change and ocean acidification.[38,110,111] The development of climate-ready fisheries will be particularly important for coastal communities, especially those that are highly dependent on fish stocks for food and for income. Targeting and participating in an increased diversity of fisheries with more species can improve economic resilience of harvesters and fishing communities.[112,113,114] Current policies can create barriers that impede diversification,[112] but more dynamic management can enable better adaptation.[115] Even without directly accounting for climate effects, precautionary fishery management and better incentives can increase economic benefits and improve resilience.[64,65,116]

Emerging Issues and Research Gaps

Many studies have documented the impact of temperature on fish distribution and productivity, enabling initial projections of species distribution, productivity, and fishery catch potential under future warming (e.g., Cheung 2016[103]). While laboratory studies have shown that ocean acidification can impact fish and their prey,[117] there have been no studies demonstrating that acidification is currently limiting the productivity of wild fish stocks. Acidification will become an increasingly important driver of ocean ecosystem change.[39] It is likely that the primarily temperature-based projections described above are underestimating the total magnitude of future changes in fisheries. More work would be required to understand how management and climate change are likely to interact.[105,118] Climate vulnerability assessments (e.g., Hare et al.[119]) estimate which fisheries are most vulnerable in a changing climate and could be used to develop adaptation strategies and prioritize research efforts.

Key Message 3

Extreme Events

Marine ecosystems and the coastal communities that depend on them are at risk of significant impacts from extreme events with combinations of very high temperatures, very low oxygen levels, or very acidified conditions. These unusual events are projected to become more common and more severe in the future, and they expose vulnerabilities that can motivate change, including technological innovations to detect, forecast, and mitigate adverse conditions.

The first two Key Messages focused on the impacts of long-term climate trends. Ocean conditions also vary on a range of timescales, with month-to-month and year-to-year changes aligning with many biological processes in the ocean. The interaction between long-term climate change and shorter-term variations creates the potential for extreme conditions—abrupt increases in temperature, acidity, or deoxygenation (Figure 9.3). Recent extreme events in U.S. waters demonstrated that these events can be highly disruptive to marine ecosystems and to the communities that depend on them. Furthermore, these events provide a window into the conditions and challenges likely to become the norm in the future.

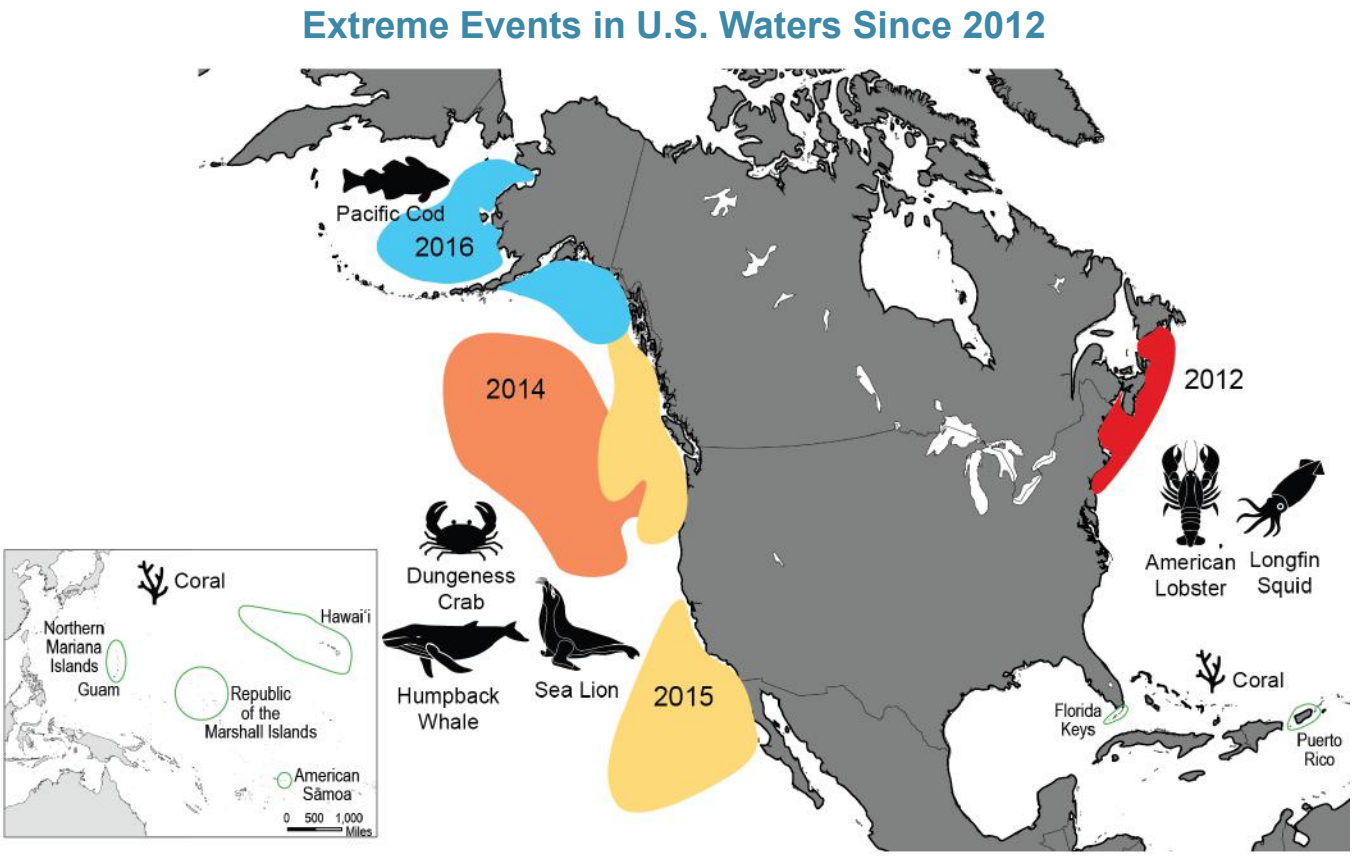


Figure 9.3: The 2012 North Atlantic heat wave was concentrated in the Gulf of Maine; however, shorter periods with very warm temperatures extended from Cape Hatteras to Iceland during the summer of 2012. American lobster and longfin squid and their associated fisheries were impacted by the event.[1] The North Pacific event began in 2014[2] and extended into shore in 2015[3,4] and into the Gulf of Alaska in 2016,[5,6] leading to a large bloom of toxic algae that impacted the Dungeness crab fishery and contributed directly and indirectly to deaths of sea lions and humpback whales. U.S. coral reefs that experienced moderate to severe bleaching during the 2015–2016 global mass bleaching event[7] are indicated by coral icons. Source: Gulf of Maine Research Institute.

Two recent events have been particularly well documented: the 2012 marine heat wave in the northwestern Atlantic Ocean (Ch. 18: Northeast, Box 18.1) and an event occurring between 2014 and 2016 in the northeastern Pacific Ocean, nicknamed the Blob (Figure 9.3) (Ch. 24: Northwest, KM 1; Ch. 25: Southwest, KM 3; Ch. 26: Alaska, KM 1). Ecosystems within these regions experienced very warm conditions (greater than 3.6°F [2°C] above the normal range) that persisted for several months or more.[1,2,3] Additionally, the very warm temperatures during the 2015–2016 El Niño led to widespread coral bleaching, including reefs off of American Sāmoa, the Marianas, Guam, Hawai'i, Florida, and Puerto Rico (Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawai'i & Pacific Islands, KM 4).[7]

Coastal communities are especially susceptible to changes in the marine environment,[110,111] and the interaction between people and the ecosystem can amplify the impacts and increase the potential for surprises (Ch. 17: Complex Systems, KM 1). In the Gulf of Maine in 2012, warm temperatures caused lobster catches to peak 3–4 weeks earlier than usual. The supply chain was not prepared for the early influx of lobsters, leading to a severe drop in price.[1] The North Pacific event, centered in 2015, featured an extensive bloom of the toxic algae *Pseudo-nitzschia*[4,120] that led to mass mortalities of sea lions and whales and the closure of the Dungeness crab fishery.[121,122] The crab fishery then reopened in the spring of 2016, normally a time when fishing effort is low. The shift in timing led to increased fishing activity during the spring migration of humpback and gray whales and thus an elevated incidence of whales becoming entangled in crab fishing gear.[122] Continued warm temperatures in the Gulf of Alaska during 2016[5] led to reduced catch of Pacific cod.[78]

Extreme events other than those related to temperature can also occur in the oceans. Short-term periods of low-oxygen, low-pH (acidified) waters have occurred more frequently along the Pacific coast during intense upwelling events.[15,123,124,125,126] The acidified waters were corrosive ($\Omega < 1$) and reduced the survival of larval Pacific oysters (*Crassostrea gigas*) in commercial hatcheries that support oyster aquaculture[127,128] and increased dissolution of the shells of pteropods, a type of planktonic snail important in many ocean ecosystems.[129,130,131,132]

Projected Impacts

The extreme temperatures experienced during both recent heat waves exposed ecosystems to conditions not expected for 50 or more years into the future, providing a window into how future warming may impact these ecosystems. In both regions, southerly species moved northward, and warmer conditions in the spring shifted the timing of biological events earlier in the year.[1,133]

In the future, the same natural patterns of climate variability associated with the heat waves in both ocean basins[3,134,135,136,137] will continue to occur on top of changing trends in average conditions, leading to more extreme events relative to current averages.[138]

Human-caused climate change likely already contributed to the events observed in 2012 and 2015, helping drive temperatures to record levels.[139,140] Ocean acidification events such as those described along the Pacific coast are already increasing and are projected to become more intense, longer, and increasingly common.[53,141] The increase in intensity and frequency of toxic algal blooms has been linked to warm events and increasing temperatures in both the Atlantic and Pacific Oceans.[4,120,142]

Changes resulting from human activities, especially increased nutrient loads, accelerate the development of hypoxic events in many areas of the world's coastal ocean.[15,143]

Opportunities for Reducing Risk

Extreme events in the oceans can lead to significant disruptions to ecosystems and people, but they can also drive technological adaptation. Several corrosive events along the Pacific Northwest coast prompted the Pacific Coast Shellfish Growers Association to work with scientists to test new observing instruments and develop management procedures.[128] The hatcheries now monitor pH and pCO_2 (partial pressure of carbon dioxide) in real time and adjust seawater intake to reduce acidity. Similar practices are being employed on the East Coast to adapt shellfish hatcheries to the increasing frequency of low-pH events associated with increased precipitation and runoff.[144]

Similarly, the need to forecast El Niño events led to the development of seasonal climate forecast systems.[145] Current modeling systems make it possible to forecast temperature, pH, and oxygen conditions several months into the future.[101,102,146,147,148] Operational forecasts are also being developed for harmful algal blooms[149] and for the timing of Maine's lobster fishery.[150] Further engagement with users would improve the utility of these emerging forecasts.[101,148]

Emerging Issues and Research Gaps

The recent extreme events in U.S. ocean waters were the result of the interaction between natural cycles and long-term climate trends. As carbon emissions drive average temperatures higher and increase ocean acidification, natural climate cycles will occur on top of ocean conditions that are warmer, acidified, and have generally lower oxygen levels. A major uncertainty is whether these natural cycles will function in the same way in an altered climate. For example, the natural patterns of climate variability that contributed to the formation of the Blob show increasing variability in climate model projections.[3] This suggests that similar temperature events in the North Pacific may be more likely. Unusually persistent periods of warm weather led to the formation of both the North Atlantic and North Pacific heat waves.[2,134,151] Observational and modeling studies suggest that the loss of Arctic sea ice may disrupt mid-latitude atmospheric circulation patterns, making extreme weather conditions more likely (e.g., Overland et al. 2016, Vavrus et al. 2017, but see Cohen 2016[152,153,154]). This mechanism suggests that extremes in the ocean may be more extreme in the future, even after accounting for climate trends.

Conclusion

Ocean ecosystems provide economic, recreational, and cultural opportunities for all Americans. Increasing temperatures, ocean acidification, and deoxygenation are likely to alter marine ecosystems and the important benefits and services they provide. There has been progress in developing management strategies and technological improvements that can improve resilience in the face of long-term changes and abrupt events. However, many impacts, including losses of unique coral reef and sea ice ecosystems, can only be avoided by reducing carbon dioxide emissions.

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Opening Image Credit

Coral reefs: NOAA Coral Reef Conservation Program.

Traceable Accounts

Process Description

The goal when building the writing team for the Oceans and Marine Resources chapter was to assemble a group of scientists who have experience across the range of marine ecosystems (such as coral reefs and temperate fisheries) that are important to the United States and with expertise on the main drivers of ocean ecosystem change (temperature, deoxygenation, and acidification). We also sought geographic balance and wanted a team that included early-career and senior scientists.

We provided two main opportunities for stakeholders to provide guidance for our chapter. This included a town hall meeting at the annual meeting of the Association for the Sciences of Limnology and Oceanography and a broadly advertised webinar hosted by the National Oceanic and Atmospheric Administration. Participants included academic and government scientists, as well as members of the fisheries and coastal resource management communities. We also set up a website to collect feedback from people who were not able to participate in the town hall or the webinar.

An important consideration in our chapter was what topics we would cover and at what depth. We also worked closely with the authors of Chapter 8: Coastal to decide which processes and ecosystems to include in which chapter. This led to their decision to focus on the climate-related physical changes coming from the ocean, especially sea level rise, while our chapter focused on marine resources, including intertidal ecosystems such as salt marshes. We also decided that an important goal of our chapter was to make the case that changing ocean conditions have a broad impact on the people of the United States. This led to an emphasis on ecosystem services, notably fisheries and tourism, which are easier to quantify in terms of economic impacts.

Key Message 1

Ocean Ecosystems

The Nation's valuable ocean ecosystems are being disrupted by increasing global temperatures through the loss of iconic and highly valued habitats and changes in species composition and food web structure (*very high confidence*). Ecosystem disruption will intensify as ocean warming, acidification, deoxygenation, and other aspects of climate change increase (*very likely, very high confidence*). In the absence of significant reductions in carbon emissions, transformative impacts on ocean ecosystems cannot be avoided (*very high confidence*).

Description of evidence base

Ocean warming has already impacted biogenically built habitats. Declines in mussel beds, kelp forests, mangroves, and seagrass beds, which provide habitat for many other species, have been linked to ocean warming and interactions of warming with changes in oxygen levels or other stressors (see Ch. 27: Hawai'i & Pacific Islands, Key Message 4 for impacts on mangrove systems in the Pacific Islands).[155,156,157,158] Sea level rise will continue to reduce the extent of many estuarine and coastal habitats (for example, salt marshes, seagrass beds, and shallow coral reefs) in locations where they fail to accrete quickly enough to outpace rising seas.[159,160] The composition and timing

of phytoplankton blooms are shifting, and dominant algal species are changing, which can cause bottom-up changes in food web structure.[17,18,161]

Some of the most apparent ecosystem changes are occurring in the warmest and coldest ocean environments, in coral reef and sea ice ecosystems. Live coral cover in coral reef ecosystems around the world has declined from a baseline of about 50%–75% to only 15%–20% (the current average for most regions; see Bruno & Valdivia 2016; Eddy et al. 2018[69,162]), primarily due to ocean warming.[163,164] Exposure to water temperatures just a few degrees warmer than normal for a given reef can cause corals to bleach; bleached corals have expelled their colorful symbiotic dinoflagellate algae, and the lack of algae can partially or wholly kill coral colonies.[165] Over the past four decades, warming has caused annual average Arctic sea ice extent to decrease between 3.5% and 4.1% per decade; sea ice melting now begins at least 15 days earlier than it did historically (Ch. 26: Alaska, KM 1).[166,167,168] Several studies have shown that sea ice loss has changed food web dynamics, caused diet shifts, and contributed to a continued decline of some Arctic seabird and mammal populations.[49,169,170,171,172] For instance, polar bear litter sizes have already declined and are projected to decline further; models suggest that sea ice breaking up two months earlier than the historical normal will decrease polar bear pregnancy success in Huntington Bay by 55%–100%.[173,174]

Species differ in their response to warming, acidification, and deoxygenation. This imbalance in sensitivity will lead to ecosystem reorganization, as confirmed by a number of recent ecosystem models focused on phytoplankton[17,175,176] and on entire food webs.[40,68,177,178,179,180] Local extinction and range shifts of marine species due to changes in environmental conditions have already been well documented, as have the corresponding effects on community structure.[32,81]

Global-scale coral bleaching events in 1987, 1998, 2005, and 2015–2016 have caused a rapid and dramatic reduction of living coral cover; as the regularity of these events increases, their effects on ecosystem integrity may also increase.[7,164,181,182] Warming increases the likelihood of coral disease outbreaks and reduces coral calcification, reproductive output, and a number of other biological processes related to fitness.[183,184] Under the higher scenario (RCP8.5), all shallow tropical coral reefs will be surrounded by water with $\Omega < 3$ by the end of this century.[59] Laboratory research finds that many coral species are negatively impacted by exposure to high CO_2 conditions,[185,186,187] and field research conducted near geologic CO_2 vents have found that exposure to high CO_2 conditions changes some, but not all, coral communities.[188,189,190,191] Sea ice loss in the Arctic is expected to continue through this century, very likely resulting in nearly sea ice-free late summers by the middle of the century (Ch. 26: Alaska, KM 1).[166] Ice-free summers will result in the loss of habitats in, on, and under the ice and the emergence of a novel ecosystem in the Arctic.[51] Arctic waters are also acidifying faster than expected, in part due to sea ice loss.[192]

Conservation measures, such as ecosystem-based fisheries management (Key Message 2) and marine-protected areas that reduce or respond to these other stressors, can increase resilience;[66,67] however, these approaches have limits and can only slow the impact of climate change and ocean acidification.[68] Ocean warming, acidification, and deoxygenation, among other indirect stressors, will lead to alterations in species distribution, the decline of some species' calcification, and mismatched timing of prey–predator abundance that cannot be fully avoided with management strategies.[33,193] Coral bleaching occurs on remote reefs, suggesting that even pristine reefs will be impacted in a warmer, more acidified ocean.[69,70] Without substantial reductions in CO_2

emissions, massive and sometimes irreversible impacts are very likely to occur in marine ecosystems, including those vital to coastal communities.[57]

Major uncertainties

Further research is necessary to fully understand how multiple stressors, such as temperature, ocean acidification, and deoxygenation, will concurrently alter marine ecosystems in U.S. waters. More research on the interaction of multiple stressors and in scaling results from individual to population or community levels is needed.[27,194,195,196]

Most species have some capacity to acclimate to changes in thermal and chemical conditions, depending on the rate and magnitude at which conditions change, and there may be enough genetic variation in some populations to allow for evolution.[73,197,198,199] Some research suggests that only microbes have the ability to acclimate to the expected anthropogenic temperature and pH changes, suggesting a reduction in the diversity and abundance of key species and a change in trophic energy transfer, which underpin ecosystem function of the modern ocean.[33]

Description of confidence and likelihood

The amount of research and agreement among laboratory results, field observations, and model projections demonstrate *very high confidence* that ecosystem disruption has occurred due to climate change, particularly in tropical coral reef and sea ice-associated ecosystems due to the global increase of ocean temperatures. It is *very likely* that ecosystem disruption will intensify later this century under continued carbon emissions, as there is *very high confidence* that warming, acidification, deoxygenation, and other aspects of climate change will accelerate. While conservation and management practices can build resilience in some ecosystems, there is *very high confidence* that only reductions in carbon emissions can avoid significant ecosystem disruption, especially in coral reef and sea ice ecosystems.

Key Message 2

Marine Fisheries

Marine fisheries and fishing communities are at high risk from climate-driven changes in the distribution, timing, and productivity of fishery-related species (*likely, high confidence*). Ocean warming, acidification, and deoxygenation are projected to increase these changes in fishery-related species, reduce catches in some areas, and challenge effective management of marine fisheries and protected species (warming: *very likely, very high confidence;* acidification and deoxygenation: *likely, high confidence*). Fisheries management that incorporates climate knowledge can help reduce impacts, promote resilience, and increase the value of marine resources in the face of changing ocean conditions.

Description of evidence base

Most evidence of the impacts of climate variability on U.S. living marine resources comes from numerous studies examining the response of these species to variability in ocean temperature. There is strong evidence that fluctuations in ocean temperature, either directly or indirectly via impacts to food web structure, are associated with changes in the distribution,[31,79,80,81]

productivity,[74,75,76,77,200,201,202] and timing of key life-history events, such as the spawning[1,31,88,89] of fish and invertebrates in U.S. waters. These temperature-driven changes in the dynamics of living marine resources in turn affect commercial fisheries catch quantity,[79] composition,[203] and fisher behavior.[1,83,204,205] Beyond temperature, there is robust evidence from experimental studies demonstrating the impacts of oxygen and pH variability on the productivity of marine fish and invertebrates.[55,117,206] However, studies linking changes in oxygen or pH to variations in fisheries and aquaculture dynamics in the field are few and are mainly regional and/or specific to localized deoxygenation or acidification events.[71,128,207]

These observational and experimental studies have provided the foundation for the development of models projecting future impacts of changing climate and ocean conditions on fisheries. Global and regional applications of such models provide strong evidence that changes in future ocean warming will alter fisheries catches in U.S. waters.[64,100,103,208,209,210] The projected decrease in catch potential in the tropics and the projected increase in high-latitude regions under both RCP4.5 and RCP8.5 scenarios are robust to model structural uncertainty[103] and are consistent across modeling approaches.[100,103,209,210] In addition, there is moderate evidence from regional ecosystem and single-species models of reduced future catch in specific U.S. regions from future ocean acidification.[40,95,177,179,211]

Fisheries management in the United States has become increasingly effective at setting sustainable harvest levels, and the number of U.S. fisheries that are overfished or subjected to overfishing has declined in most regions.[212] Science-informed management in general has been shown to be effective in improving ecosystem status[107] and has been projected to greatly improve the benefits from marine resources.[65] Climate change presents new challenges to management systems, as some species move across management boundaries and away from traditional fishing grounds and as productivity patterns shift. Management approaches that do not consider climate-driven ecosystem changes can lead to overfishing when the environment shifts rapidly.[76,213] Some measures have been proposed to make the fisheries management system more climate ready.[84,105,214] In many cases, these management strategies will include measures to allow for greater flexibility for harvesters to adapt to changing distributions and quantities of target species. Some preliminary evidence suggests that the use of climate-informed harvest rules can improve fishery sustainability in a variable environment,[102] but at present, few fisheries management decisions integrate climate-related environmental information.[215] The North Pacific Fishery Management Council is currently examining a strategic, multispecies, climate-enhanced model that informs managers how climate change and variation are expected to impact key stocks.[106]

Major uncertainties

While shifts in the productivity and distribution of living marine resources and ecosystem structure are expected to change catch potential and catch composition in U.S. regions, many uncertainties exist. Projections of catch potential have largely been performed using dynamical bioclimatic envelope models (e.g., Cheung et al.[103]). In these models, the spatial population dynamics of fish stocks are forced by temperature (with additional net primary productivity effects on carrying capacity and pH and oxygen effects on growth) and do not include the potential for major changes in species interactions, as has previously occurred with warming events (e.g., Vergés et al.[32]) and food web structure (e.g., Fay et al.[179]). Furthermore, recent studies indicate that zooplankton and export production may serve as better indicators of carrying capacity for fisheries than

net primary productivity.[210,216] Net primary productivity trends will likely be amplified by higher trophic levels, such as zooplankton and ultimately fish; thus, trends in catch potential projected from primary productivity alone may underestimate future changes.[210] These models also do not consider the potential for evolutionary adaptation of marine species. Uncertainties in projections are particularly high for primary productivity, oxygen, and pH, especially at regional and coastal scales,[217,218,219] but these uncertainties are not typically incorporated into projected catch trends. In terms of the economic impacts on consumers, there is also uncertainty about how potential decreases in the catch of some species will impact net revenues, as lower quantities will be compensated in some cases by increased prices paid by consumers (e.g., Seung and Ianelli[94]). Fish prices are expected to increase very modestly over the next decade, yet there are great uncertainties in longer-term prices based on uncertainty about climate, economic growth, and the effectiveness of management in fisheries around the world.[220]

In addition, climate change is only one of many stressors affecting fish dynamics. Future fish distribution, abundance, and productivity will depend on the interaction between these stressors, including fishing and climate-related stressors. Conceptually and empirically, it is clear that fishers are responding to a wide diversity of factors and may not narrowly follow shifting fish populations.[83,221,222] The development of management measures that respond rapidly to dramatic shifts in environmental factors that impact recruitment, productivity, and distribution will also reduce the potential impacts of climate change by avoiding overfishing in times of environmental stress.

Description of confidence and likelihood

There is *high confidence* that climate change-driven alterations in the distribution, timing, and productivity of fishery-related species will *likely* lead to increased risk to the Nation's valuable marine fisheries and fishing communities. There is *very high confidence* that future ocean warming will *very likely* increase these changes in fishery-related species, reduce catches in some areas, and challenge effective management of marine resources. There is *high confidence* that ocean acidification and deoxygenation will *likely* reduce catches in some areas, which will challenge effective management of marine fisheries and protected species.

Key Message 3

Extreme Events

Marine ecosystems and the coastal communities that depend on them are at risk of significant impacts from extreme events with combinations of very high temperatures, very low oxygen levels, or very acidified conditions. These unusual events are projected to become more common and more severe in the future (*very likely, very high confidence*), and they expose vulnerabilities that can motivate change, including technological innovations to detect, forecast, and mitigate adverse conditions.

Description of evidence base

Marine heat waves have been described as regions of large-scale and persistent positive sea surface temperature anomalies that can vary in size, distribution, timing, and intensity akin to

their terrestrial counterparts.[137,223] Well-documented marine heat waves have recently occurred in the northwest Atlantic in 2012[1,134,151] and the North Pacific in 2014–2016.[2,6]

Each of these events resulted in documented impacts to ecosystems and, in many cases, to the human communities to which they were connected. The recent major events in the U.S. northwest Atlantic and North Pacific led to economic challenges in the American lobster, Dungeness crab, and Gulf of Alaska Pacific cod fisheries.[1,2,78,224]

Abrupt warming can induce other ecosystem-level impacts. The North Pacific event featured an extensive bloom of the harmful algae *Pseudo-nitzschia*[4,120] that led to mass mortalities of sea lions and whales and the closure of the Dungeness crab fishery. The increase in intensity and occurrence of these toxic algal blooms has been linked to warm events in both the Atlantic and the Pacific.[4,120,142] Abrupt warming was inferred to trigger the expansion of the North Pacific oxygen minimum zone through reduced oxygen solubility and increased marine productivity.[225]

Extreme events with corrosive ($\Omega < 1$) and/or low oxygen conditions can occur when deep waters, which are generally corrosive and have low oxygen levels, are brought into the coastal area during upwelling. They can also occur in response to the delivery of corrosive freshwater from the landscape, ice melting, and storms. These conditions now occur more frequently in coastal waters of the Pacific coast of the United States.[39,126,131,226,227,228,229,230,231] Such events have led to the elevated mortality of coastal shellfish in hatcheries[128] and die-offs of crabs and other animals living on the ocean bottom.[123]

Heat wave, high-acidity, and low-oxygen events are all produced by variability in the system occurring on timescales ranging from days to years. For example, recent marine heat waves have been linked to natural climate modes such as the North Atlantic Oscillation, Atlantic Multidecadal Oscillation, Pacific Decadal Oscillation, or North Pacific Gyre Oscillation, which change over several years.[3,137] Persistent weather patterns lasting several months can further amplify conditions in the ocean, leading to extreme conditions.[2,134,151] These climate modes and atmospheric conditions occur on top of the long-term trends caused by global climate change. Thus, as climate change progresses, events with temperatures above a certain level, oxygen below a certain level, or pH below a specified level will occur more frequently and will last longer.[56,141,146,232]

The intensity of corrosive events along the upwelling margin of the Pacific coast of the United States is increasing due to more intense winds over the past decade and ocean acidification.[15,53,123,125] In Alaska waters, these events are associated with freshwater inputs and storm events that may also have a link to climate change.[226,227,228,229,230,233]

There is ample evidence that extreme events motivate adaptive change in human systems. For example, Hurricane Katrina and Superstorm Sandy motivated communities near the affected areas to expand planning against future storms.[234,235] The 2012 North Atlantic heat wave prompted the development of a forecast system to help Maine's lobster fishery avoid future supply chain disruptions (Ch. 18: Northeast).[150] The impact of corrosive waters on shellfish hatcheries in the Pacific Northwest motivated the development of new technology to monitor and manage water chemistry in shellfish hatcheries.[128]

Major uncertainties

The description above assumes that natural modes of climate variability remain the same and can be simply added to baseline conditions set by the global climate. There is evidence that some natural climate modes may change in the future. As mentioned in the narrative, the climate oscillations linked to the 2014–2016 event in the North Pacific increase in amplitude in climate model projections.[3,135,236] This suggests that extreme events will be more likely in the future, even without accounting for the shift to a warmer temperature baseline. Declines in Arctic sea ice are also hypothesized to impact future climate variability by causing the atmospheric jet stream to get stuck in place for days and weeks (e.g., Overland et al. 2016, Vavrus et al. 2017, but see Cohen 2016[152,153,154]). This has the potential to create persistent warm (where the jet stream is displaced to the north) and cold (where the jet stream moves south) weather conditions over North America.[152,153] These conditions are similar to the precursors to both the northwestern Atlantic and North Pacific heat waves.[2,134]

For biogeochemistry, other factors may amplify the global changes at the regional level as well, especially in the coastal environment. These factors include local nutrient runoff, freshwater input, glacial runoff, spatial variability in retentive mechanisms, variability in upwelling strength, cloud cover, and stability of sedimentary deposits (for example, methane).[15,125,143,151,231,233] Most of the factors will amplify the global trends toward lower oxygen and pH, leaving these estimates to be conservative. In addition, temperature, oxygen, and pH have synergistic effects that provide some uncertainties in the projected events.[56]

Description of confidence and likelihood

Because there is *very high confidence* and *very high likelihood* that oceans will get warmer, more acidified, and have lower oxygen content in response to elevated atmospheric carbon dioxide levels,[15] it is *very likely* and there is *very high confidence* that extreme events will occur with increased intensity and frequency in the future.[6,138,141,232,237]

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10 Agriculture and Rural Communities

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10 Agriculture and Rural Communities

Tyringham, Massachusetts

Key Message 1

Reduced Agricultural Productivity

Food and forage production will decline in regions experiencing increased frequency and duration of drought. Shifting precipitation patterns, when associated with high temperatures, will intensify wildfires that reduce forage on rangelands, accelerate the depletion of water supplies for irrigation, and expand the distribution and incidence of pests and diseases for crops and livestock. Modern breeding approaches and the use of novel genes from crop wild relatives are being employed to develop higher-yielding, stress-tolerant crops.

Key Message 2

Degradation of Soil and Water Resources

The degradation of critical soil and water resources will expand as extreme precipitation events increase across our agricultural landscape. Sustainable crop production is threatened by excessive runoff, leaching, and flooding, which results in soil erosion, degraded water quality in lakes and streams, and damage to rural community infrastructure. Management practices to restore soil structure and the hydrologic function of landscapes are essential for improving resilience to these challenges.

Key Message 3

Health Challenges to Rural Populations and Livestock

Challenges to human and livestock health are growing due to the increased frequency and intensity of high temperature extremes. Extreme heat conditions contribute to heat exhaustion, heatstroke, and heart attacks in humans. Heat stress in livestock results in large economic losses for producers. Expanded health services in rural areas, heat-tolerant livestock, and improved design of confined animal housing are all important advances to minimize these challenges.

Key Message 4

Vulnerability and Adaptive Capacity of Rural Communities

Residents in rural communities often have limited capacity to respond to climate change impacts, due to poverty and limitations in community resources. Communication, transportation, water, and sanitary infrastructure are vulnerable to disruption from climate stressors. Achieving social resilience to these challenges would require increases in local capacity to make adaptive improvements in shared community resources.

Executive Summary

In 2015, U.S. agricultural producers contributed $136.7 billion to the economy and accounted for 2.6 million jobs. About half of the revenue comes from livestock production. Other agriculture-related sectors in the food supply chain contributed an additional $855 billion of gross domestic product and accounted for 21 million jobs.

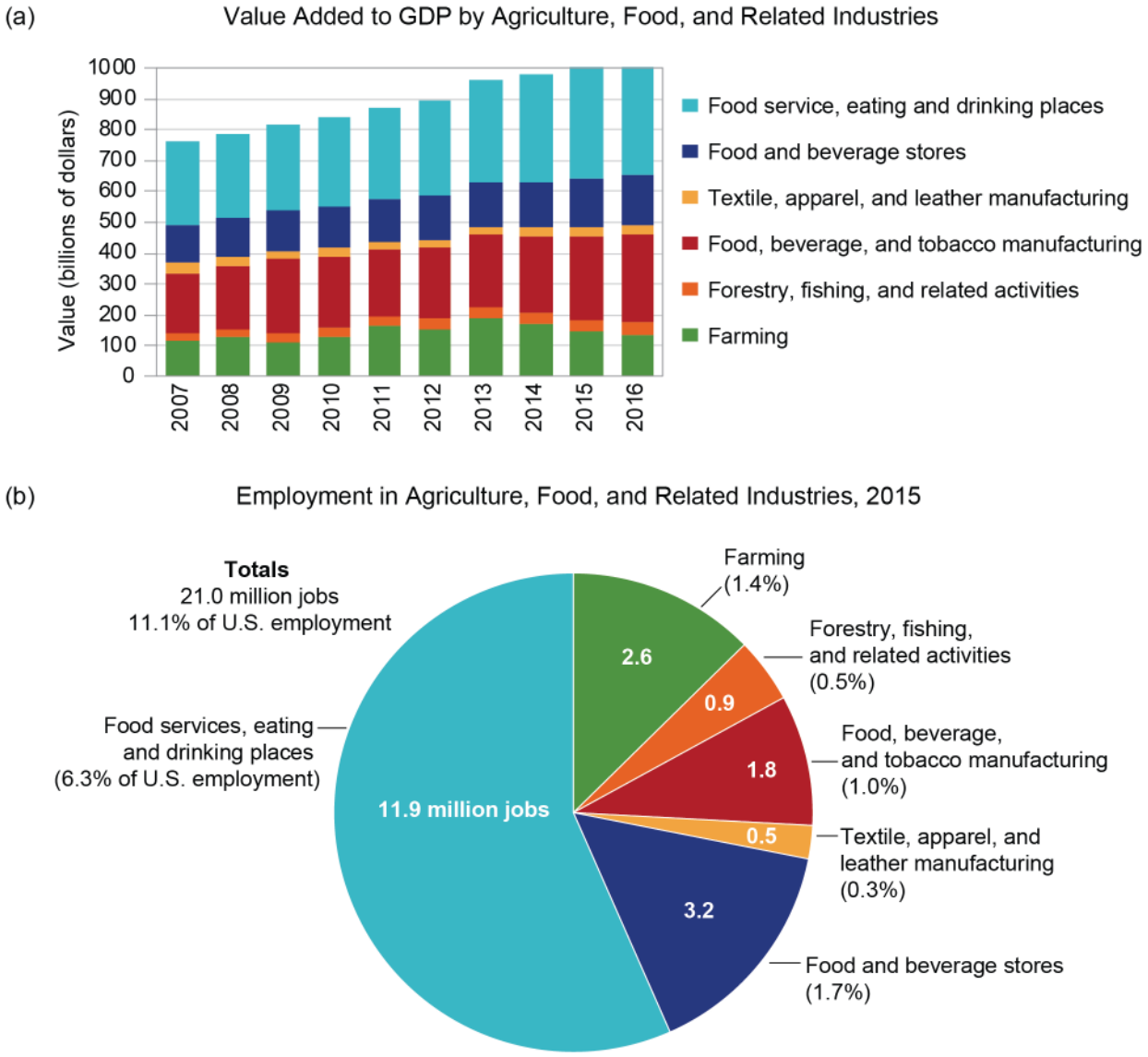
In 2013, about 46 million people, or 15% of the U.S. population, lived in rural counties covering 72% of the Nation's land area. From 2010 to 2015, a historic number of rural counties experienced population declines, and recent demographic trends point to relatively slow employment and population growth in rural areas as well as high rates of poverty. Rural communities, where livelihoods are more tightly interconnected with agriculture, are particularly vulnerable to the agricultural volatility related to climate.

Climate change has the potential to adversely impact agricultural productivity at local, regional, and continental scales through alterations in rainfall patterns, more frequent occurrences of climate extremes (including high temperatures or drought), and altered patterns of pest pressure. Risks associated with climate change depend on the rate and severity of the change and the ability of producers to adapt to changes. These adaptations include altering what is produced, modifying the inputs used for production, adopting new technologies, and adjusting management strategies.

U.S. agricultural production relies heavily on the Nation's land, water, and other natural resources, and these resources are affected directly by agricultural practices and by climate. Climate change is expected to increase the frequency of extreme precipitation events in many regions in the United States. Because increased precipitation extremes elevate the risk of surface runoff, soil erosion, and the loss of soil carbon, additional protective measures are needed to safeguard the progress that has been made in reducing soil erosion and water quality degradation through the implementation of grassed waterways, cover crops, conservation tillage, and waterway protection strips.

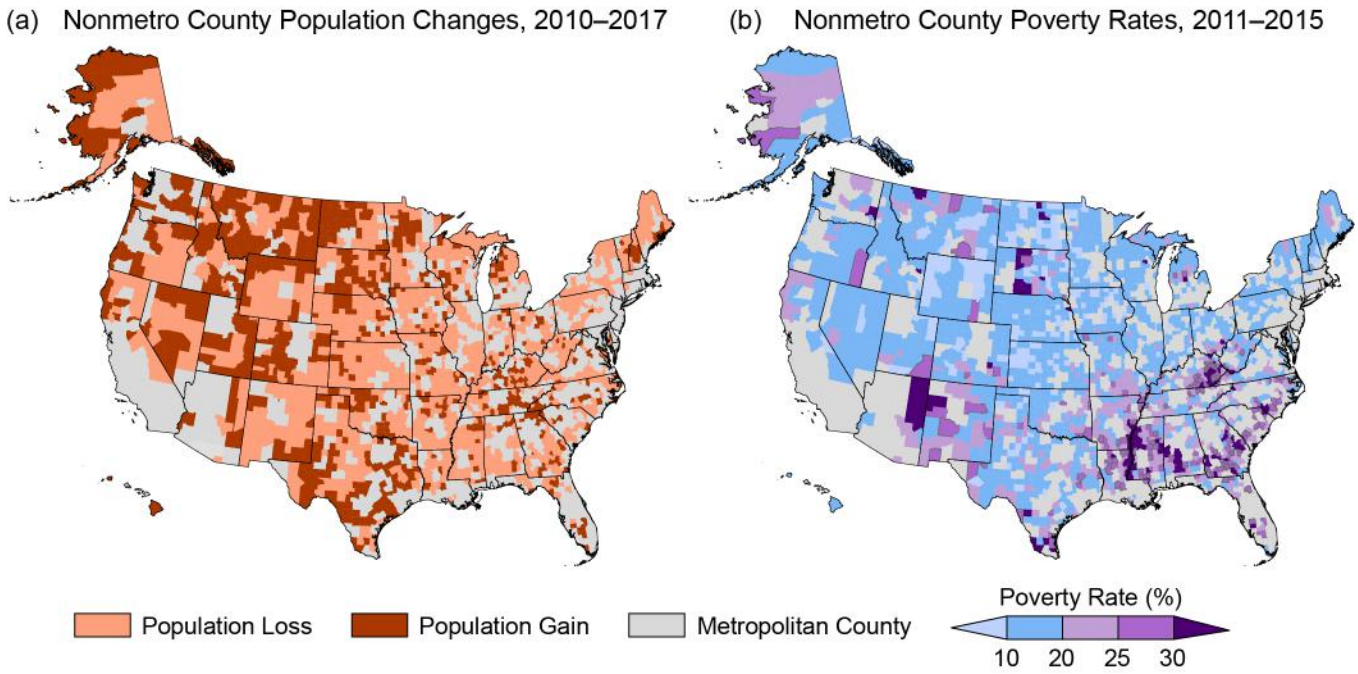
Climate change impacts, such as changes in extreme weather conditions, have a complex influence on human and livestock health. The consequences of climate change on the incidence of drought also impact the frequency and intensity of wildfires, and this holds implications for agriculture and rural communities. Rural populations are the stewards of most of the Nation's forests, watersheds, rangelands, agricultural land, and fisheries. Much of the rural economy is closely tied to the natural environment. Rural residents, and the lands they manage, have the potential to make important economic and conservation contributions to climate change mitigation and adaptation, but their capacity to adapt is impacted by a host of demographic and economic concerns.

Agricultural Jobs and Revenue



The figure shows (a) the contribution of agriculture and related sectors to the U.S. economy and (b) employment figures in agriculture and related sectors (as of 2015). Agriculture and other food-related value-added sectors account for 21 million full- and part-time jobs and contribute about $1 trillion annually to the United States economy. *From Figure 10.1 (Source: adapted from Kassel et al. 2017[1]).*

Population Changes and Poverty Rates in Rural Counties



The figure shows county-level (a) population changes for 2010–2017 and (b) poverty rates for 2011–2015 in rural U.S. communities. Rural populations are migrating to urban regions due to relatively slow employment growth and high rates of poverty. Data for the U.S. Caribbean region were not available at the time of publication of this report. *From Figure 10.2 (Sources: [a] adapted from ERS 2018[2]; [b] redrawn from ERS 2017[3]).*

State of the Agriculture and Rural Communities Sectors

U.S. farmers and ranchers are among the most productive in the world. The agricultural sector makes an important contribution to the U.S. economy, from promoting food and energy security to providing jobs in rural communities across the country. In 2015, U.S. farms contributed $136.7 billion to the economy, accounting for 0.76% of gross domestic product (GDP) and 2.6 million jobs (1.4% of total U.S. employment; Figure 10.1).[1] About half of the farm revenue comes from livestock production. Other agriculture- and food-related value-added sectors contributed an additional 4.74% ($855 billion) of GDP and accounted for 21 million full- and part-time jobs (11.1% of U.S. employment). U.S. agriculture enjoys a trade surplus in which the value of agricultural exports (both bulk and high-value products) accounts for more than 20% of total U.S. agricultural production. Top high-value exports include feedstocks, livestock products, horticulture products, and oilseeds and oilseed products, and these exports help support rural communities across the Nation.

A major portion of rural communities in the United States depend on agriculture and other related industries as economic drivers. During 2010–2012, a total of 444 counties were classified as farming dependent, of which 391 were rural counties.[4] In 2013, about 46 million people, or 15% of the U.S. population, lived in rural counties, covering 72% of the Nation's land area. From 2010 to 2017, a historic number of rural counties in the United States experienced population declines due to persistent outmigration of young adults.[2] However, some counties in the Northern Great Plains reversed decades of population loss to grow at a modest rate due to the energy boom in that region. Recent demographic trends point to relatively slow employment and population growth in rural areas, as well as higher rates of poverty in rural compared to urban regions (Figure 10.2).[1,5,6,7]

U.S. agricultural production relies heavily on the Nation's land, water, and other natural resources.[8] In 2012, about 40%, or 915 million acres, of U.S. land was farmland, of which 45.4% was permanent pasture, 42.6% was cropland, and 8.4% was woodland.[9] Only about 6% of the farmland was irrigated. Agricultural land use can change over time,[10,11] and these changes are sometimes reversible, such as when shifting between cropland and pastureland (Ch. 22: N. Great Plains, Table 22.3, Figure 22.4), and sometimes irreversible, such as when agricultural land is converted to urban uses.[12] These natural resource bases are affected continually by agricultural production practices and climate change.[13,14,15,16]

Bioenergy cropping is increasing and remains a major focus of research to develop appropriate dedicated feedstocks for different regions of the United States.[17,18,19,20,21,22] Crop residue harvest, particularly from corn, has the potential to provide additional income streams to producers and rural communities, but the impact on soil carbon sequestration and greenhouse gas (GHG) emissions indicates that only part of the residue can be harvested sustainably.[23,24,25,26] Biochar, a by-product of cellulosic bioenergy production, holds potential as a soil amendment[27,28] that in some soils provides a GHG mitigation[29] and adaptation benefit. However, many questions remain on how to develop sustainable crop- and grass-based bioenergy systems within a region.[30,31,32]

Technological advancements through concerted public and private efforts and the increasing availability of inputs (such as fertilizers, pesticides, and feed additives) have led to significant improvements in productivity while reducing agriculture's environmental

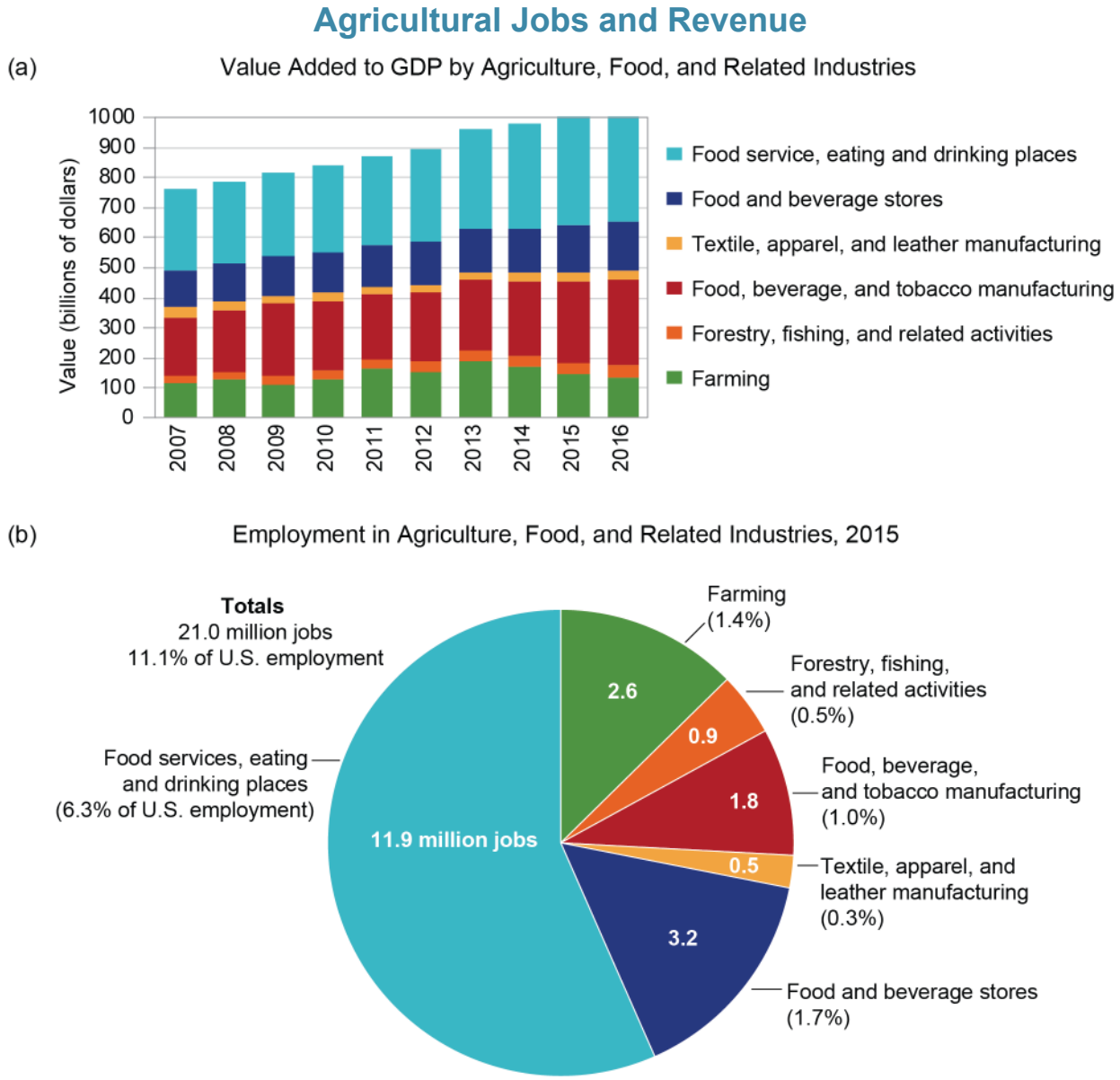


Figure 10.1: The figure shows (a) the contribution of agriculture and related sectors to the U.S. economy and (b) employment figures in agriculture and related sectors (as of 2015). Agriculture and other food-related value-added sectors account for 21 million full- and part-time jobs and contribute about $1 trillion annually to the United States economy. Source: adapted from Kassel et al. 2017.[1]

footprint.[33,34,35] However, there are some major challenges to the future of agriculture and food security.[36] The agricultural sector accounted for about 9% of the Nation's total GHG emissions in 2015,[37] so reducing emissions in the agriculture sector could have a significant impact on total U.S. emissions. Nonetheless, agriculture is one of the few sectors with the potential for significant increases in carbon sequestration to offset GHG emissions. Furthermore, water quality degradation, including eutrophication (an overload of nutrients) in the Great Lakes and coastal water bodies (for example, the northern Gulf of Mexico and the Chesapeake Bay) (see Ch. 18: Northeast, Box 18.6; Ch. 21: Midwest, Box 21.1; Ch. 23: S. Great Plains, KM 3), remains an ongoing challenge.

The current state of agricultural systems in different regions of the United States is the result of continuous efforts made by farmers, ranchers, researchers, and extension

Population Changes and Poverty Rates in Rural Counties

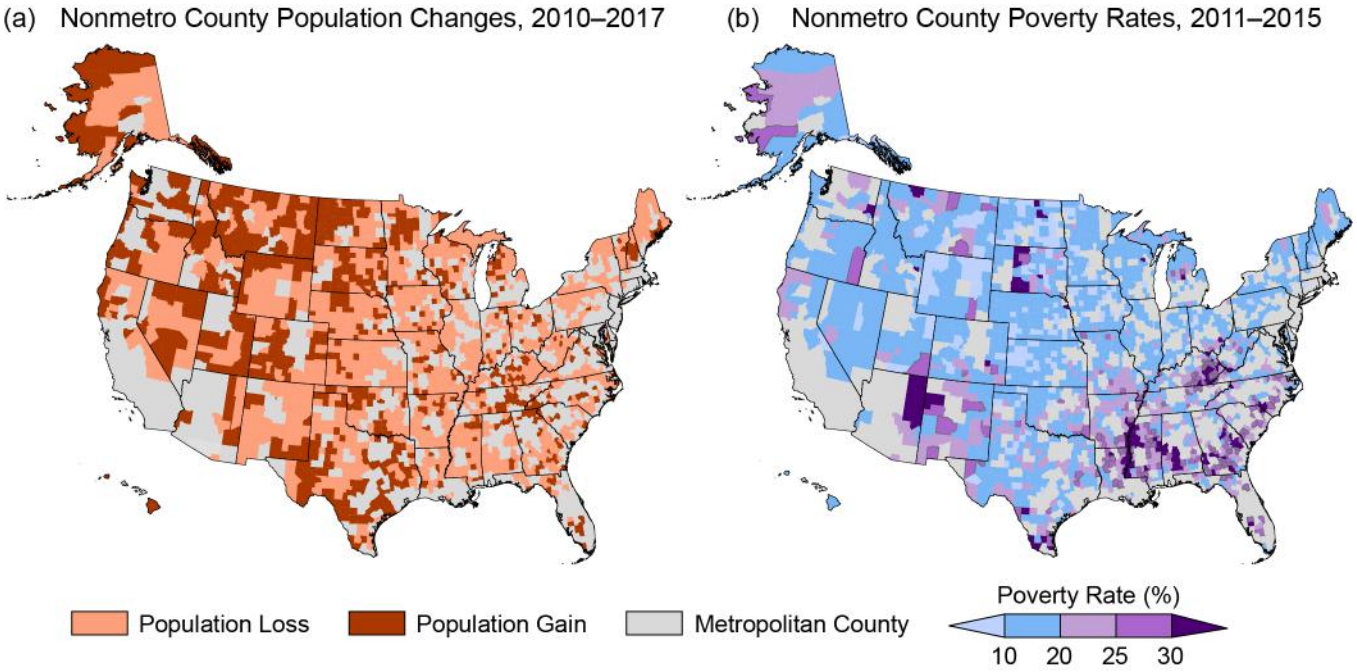


Figure 10.2: The figure shows county-level (a) population changes for 2010–2017 and (b) poverty rates for 2011–2015 in rural U.S. communities. Rural populations are migrating to urban regions due to relatively slow employment growth and high rates of poverty. Data for the U.S. Caribbean region were not available at the time of publication. Sources: (a) adapted from ERS 2018[2]; (b) redrawn from ERS 2017.[3]

specialists to identify opportunities, practices, and strategies that are viable in different climates. However, any change in the climate poses a major challenge to agriculture through increased rates of crop failure, reduced livestock productivity, and altered rates of pressure from pests, weeds, and diseases.[38,39] Rural communities, where economies are more tightly interconnected with agriculture than with other sectors, are particularly vulnerable to the agricultural volatility related to climate.[40]

Climate changes projected by global climate models are consistent with observed climate changes of concern to agriculture (Ch. 2: Climate).[41,42,43] Climate change has the potential to adversely impact agricultural productivity at local, regional, and continental scales.[44] Crop and livestock production in certain regions will be adversely impacted both by direct effects of climate change (such as increasing trends in daytime and nighttime temperatures; changes in rainfall patterns; and more frequent climate extremes, flooding, and drought) and consequent secondary effects (such as increased weed, pest, and disease pressures; reduced crop and forage production and quality; and damage to infrastructure). While climate change impacts on future agricultural production in specific regions of the United States remain uncertain, the ability of producers to adapt to climate change through planting decisions, farming practices, and use of technology can reduce its negative impact on production (Ch. 21: Midwest, Case Study "Adaptation in Forestry").[45]

Risks associated with climate changes depend on the rate and severity of the changes and the ability of producers to adapt to changes. The severity of financial risks also depends on changes in food prices as well as local-to-global trade levels, as production and consumption patterns will likely be altered due to climate change.[10,46] Many countries are already experiencing rapid price increases for basic

food commodities, mainly due to production losses associated with more frequent weather extremes and unpredictable weather events. The United States is a major exporter of agricultural commodities,[47] and a disruption in its agricultural production will affect the agricultural sector on a global scale. Food security, which is already a challenge across the globe, is likely to become an even greater challenge as climate change impacts agriculture.[48,49] Food security will be further challenged by projected population growth and potential changes in diets as the world seeks to feed a projected 9.8 billion people by 2050.[50,51,52]

In the late 1900s, U.S. agriculture started to develop significant capacities for adaptation to climate change, driven largely by public-sector investment in agricultural research and extension.[53] Currently, there are numerous adaptation strategies available to cope with adverse impacts of climate change.[38,54,55] These include altering what is produced in a region, modifying the inputs used for production, adopting new technologies, and adjusting management strategies. Crop management strategies include the selection of crop varieties/species that meet changes in growing degree days and changes in requirements for fertilizer rates, timing, and placement to match plant requirements.[56] Adaptation strategies also include changes in crop rotation, cover crops, and irrigation management.[57,58,59,60,61,62] With changes to rainfall patterns that greatly impact the environment, wider use of proven technologies will be required to prevent soil erosion, waterlogging, and nutrient losses.[44,63] Adaptation strategies for sustaining and improving livestock production systems include managing heat stress by altering diets,[64,65,66,67,68,69,70] providing adequate shade and clean drinking water supplies,[71,72] monitoring stock rates continuously to match forage availability,[73,74,75] altering the timing of feeding/grazing and reproduction,[76] and selecting the species/breeds that match climatic conditions.[54,77] Other strategies to reduce climate change impacts include integrated pest and disease management,[78,79] the use of climate forecasting tools,[80] and crop insurance coverage to reduce financial risk.[44,81,82] These strategies have proven effective as evidenced by continued productivity growth and efficiency. The proper implementation of combinations of these strategies has the potential to effectively manage negative impacts of moderate climate change. However, these approaches have limits under severe climate change impacts.[66,83,84,85]

Key Message 1

Reduced Agricultural Productivity

Food and forage production will decline in regions experiencing increased frequency and duration of drought. Shifting precipitation patterns, when associated with high temperatures, will intensify wildfires that reduce forage on rangelands, accelerate the depletion of water supplies for irrigation, and expand the distribution and incidence of pests and diseases for crops and livestock. Modern breeding approaches and the use of novel genes from crop wild relatives are being employed to develop higher-yielding, stress-tolerant crops.

Climate projections to the year 2100 suggest that increases are expected in the incidence of drought and elevated growing-season temperatures.[86] Elevated temperatures play a critical role in increasing the rate of drought onset, overall drought intensity, and drought impact through altered water availability and demand.[87,88] Increased evaporation rates caused by high temperatures, in association with drought, will exacerbate plant stress,[89] yield reduction,[90,91,92] fire risks,[93,94,95,96] and depletion of surface and groundwater resources.[97,98,99,100]

Soil carbon, important for enhancing plant productivity through a variety of mechanisms,[101] is depleted during drought due to low biomass productivity, which in turn decreases the resilience of agroecosystems.[23] In 2012, the United States experienced a severe and extensive drought, with more than two-thirds of its counties declared as disaster areas.[102] This drought greatly affected livestock, wheat, corn, and soybean production in the Great Plains and Midwest regions [44,103,104,105] and accounted for $14.5 billion in loss payments by the federal crop insurance program.[106] From 2013–2016, all of California faced serious drought conditions that depleted both reservoir and groundwater supplies. This lengthy drought, attributed in part to the influence of climate change,[88,107] resulted in the overdrawing of groundwater, primarily for irrigation, leading to large declines in aquifer levels (Ch. 3: Water, KM 1).[98,108] In 2014, the California state legislature passed the Sustainable Groundwater Management Act to develop groundwater management plans for sustainable groundwater use over the next 10–20 years.[109,110,111]

Average yields of many commodity crops (for example, corn, soybean, wheat, rice, sorghum, cotton, oats, and silage) decline beyond certain maximum temperature thresholds (in conjunction with rising atmospheric carbon dioxide [CO_2] levels), and thus long-term temperature increases may reduce future yields under both irrigated and dryland production.[37,91,92,97,103,112,113] In contrast, even with warmer temperatures, future yields for certain crops such as wheat, hay, and barley are projected to increase in some regions due to anticipated increases in precipitation and carbon fertilization.[97,114] However, yields from major U.S. commodity crops are expected to decline as a consequence of higher temperatures,[45] especially when these higher temperatures occur during critical periods of reproductive development.[115,116,117] Increasing temperatures are also projected to have an impact on specialty crops (fruits, nuts, vegetables, and nursery crops) (Ch. 25: Southwest, KM 6), although the effects will be variable depending on the crops and where they are grown.[118] Additional challenges involve the loss of synchrony of seasonal phenomena (for example, between crops and pollinators) (Ch. 7: Ecosystems; Ch. 25: Southwest, KM 6). Further, the interactive effects of rising atmospheric CO_2 concentrations, elevated temperatures, and changes in other climate factors are expected to enhance weed competitiveness relative to crops,[119] with temperature being a predominant factor.[120,121]

Irrigated agriculture is one of the major consumers of water supplies in the United States (Ch. 3: Water; Ch. 25: Southwest, KM 6). Irrigation is used for crop production in most of the western United States and since 2002 has expanded into the northern Midwest (Ch. 21: Midwest, KM 1) and Southeast (Ch. 19: Southeast, KM 4). Expanded irrigation is often proposed as a strategy to deal with increasing crop water demand due to higher trending temperatures coupled with decreasing growing-season precipitation. However, under long-term climate change, irrigated acreage is expected to decrease, due to a combination of declining water resources and a diminishing relative profitability of irrigated production.[97] Continuing or expanding existing levels of irrigation will be limited by the availability of water in many areas.[11,98,108] Surface water supplies are particularly vulnerable to shifts in precipitation and demand from nonagricultural sectors. Groundwater supplies are also in decline across major irrigated regions of the United States (see Case Study "Groundwater Depletion in the Ogallala Aquifer Region") (see also Ch. 3: Water, Figure 3.2; Ch. 25: Southwest, KM 1; Ch. 23: S. Great Plains, KM 1).

Crop productivity and quality may also be significantly reduced due to increased crop water

demand coupled with limited water availability[122,123,124] as well as increased diseases and pest infestations (Ch. 25: Southwest, KM 6).[125] The expected demand for higher crop productivity and anticipated climate change stresses have driven advancements in crop genetics.[126,127] Seed companies have released numerous crop varieties that are tolerant to heat, drought, or pests and diseases. This trend is expected to continue as new crop varieties are developed to adapt to a changing climate.[128] Recent advances in genetics have allowed researchers to access large and complex genomes of crops and their wild relatives.[129] This has the potential to reduce the time and cost required to identify and incorporate useful traits in plant breeding and to develop crops that are more resilient to climate change. Currently, the United States has the largest gene bank in the world that manages publicly held crop germplasm (genetic material necessary for plant breeding). However, progress in this area has been modest despite advances in breeding techniques.[130,131,132,133] Further, institutional factors such as intellectual property rights, and a lack of international access to crop genetic resources, are affecting the availability and utilization of genetic resources useful for adaptation to climate change.[134] Investments by commercial firms alone are unlikely to be sufficient to maintain these resources, meaning higher levels of public investment would be needed for genetic resource conservation, characterization, and use. Societal concerns over certain crop breeding technologies likely will continue, but current assessments of genetically engineered crops have shown economic benefits for producers, with no substantial evidence of animal or human health or environmental impacts.[135]

Climate-smart agriculture[136] can reduce the impacts of climate change and consequent environmental conditions on crop yield.[137,138] Not only do producers take climate forecasts into consideration when deciding what to produce and how to produce it, they also adapt management strategies to cope with expected weather conditions. For example, drought resilience can be improved by adopting high-efficiency precision irrigation technologies.[139,140,141] In order for these systems to work effectively, a network of weather stations is required in agricultural regions. Currently, 23 states have one or more publicly funded agricultural weather networks, such as the Oklahoma Mesonet[142] and the Nebraska Agricultural Water Management Network.[143]

The same aspects of climate change that affect the incidence of drought also affect the frequency and intensity of wildfires, which pose major risks to agriculture and rural communities. Grassland, rangeland, and forest ecosystems, which support ruminant livestock production, represent more than half of the land area of the United States.[144] Wildfires are a normal occurrence in these ecosystems, and they play an important role in long-term ecosystem health. However, climate change threatens to increase the frequency and length of the wildfire season, as well as the size and extent of large fires.[95] Increasing temperatures also promote an increased spread of invasive or encroaching species,[145] which exacerbate wildfire risks. Beyond economic losses, wildfires also contribute to climate change by releasing CO_2 into the atmosphere (Ch. 6: Forests, KM 1; Ch. 13: Air Quality, KM 2). The increased extent of high-severity fire expanding into communities further reduces the capacity to provide other services and puts communities, personnel, and infrastructures at higher risk.[146,147] Tribal communities are particularly vulnerable to wildfires, due to a lack of fire-fighting resources, insufficient experienced internal staff, and remote locations (Ch. 15: Tribes).[148,149] In addition, firefighting in many tribal communities requires coordination across fire-prone landscapes with various jurisdictional

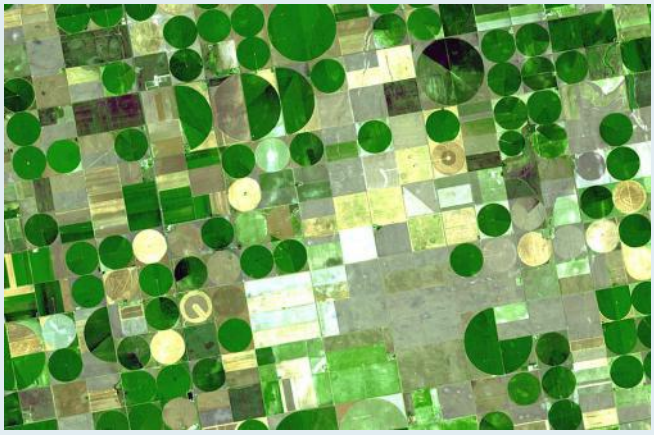
controls.[150] On average, the United States spends about $1 billion annually to fight wildfires, but it spent more than $2.9 billion in 2017 due to extreme drought conditions in some regions.[151] States, local governments, and the private sector also absorbed additional costs of firefighting and recovery. (For more on wildfires, see Ch. 5: Land Changes; Ch. 6: Forests; Ch. 15: Tribes.)

Case Study: Groundwater Depletion in the Ogallala Aquifer Region

The Ogallala Aquifer region (OAR) is one of the most productive farm belts in the world. Irrigated agriculture uses more than 95% of the groundwater extracted from the Ogallala Aquifer, and the economy of the region depends almost entirely on irrigated agriculture. Overlying states produce one-fifth of the Nation's wheat, corn, and cotton, and the southern half of the region accounts for more than one-third of the beef cattle production.[152] In 2007, the market value of agricultural products from this region was about $35 billon, which accounted for 11.6% of the total market value of agricultural products in the United States.[153]

The management of agriculture, water, and soil in the OAR has come full circle over the past century. The conversion of native grasslands for crop production in the early part of the 20th century followed by prolonged drought led to severe dust storms that became known as the Dust Bowl of the 1930s. The adoption of soil conservation methods and irrigation with Ogallala water improved soil health and reduced soil erosion while expanding the region's economy. However, major portions of the Ogallala Aquifer should now be considered a nonrenewable resource. Reduced well outputs due to excessive pumping, especially in central and southern parts of the OAR (Figure 10.3), coupled with frequent and prolonged droughts have led to recent dust storms that were similar to those of the 1930s and 1950s. Climate change is projected to further increase the duration and intensity of drought over much of the OAR in the next 50 years.[39,86] Recent advances in precision irrigation technologies,[154,155] improved understanding of the impacts of different dryland and irrigation management strategies on crop productivity,[60,156,157,158,159] and the adoption of weather-based irrigation scheduling tools[160] as well as drought-tolerant crop varieties[161] have increased the ability to cope with projected heat stress and drought conditions under climate change.[162] However, current extraction for irrigation far exceeds recharge in this aquifer, and climate change places additional pressure on this critical water resource.

Dust storm approaching Stratford, Texas (in the state's panhandle), during the Dust Bowl of the 1930s. Photo credit: NOAA George E. Marsh Album.



Satellite image showing center pivot irrigation in Finney County, Kansas. This area utilizes irrigation water from the Ogallala aquifer. Image courtesy of NASA.

Case Study: Groundwater Depletion in the Ogallala Aquifer Region, continued

Changes in the Ogallala Aquifer

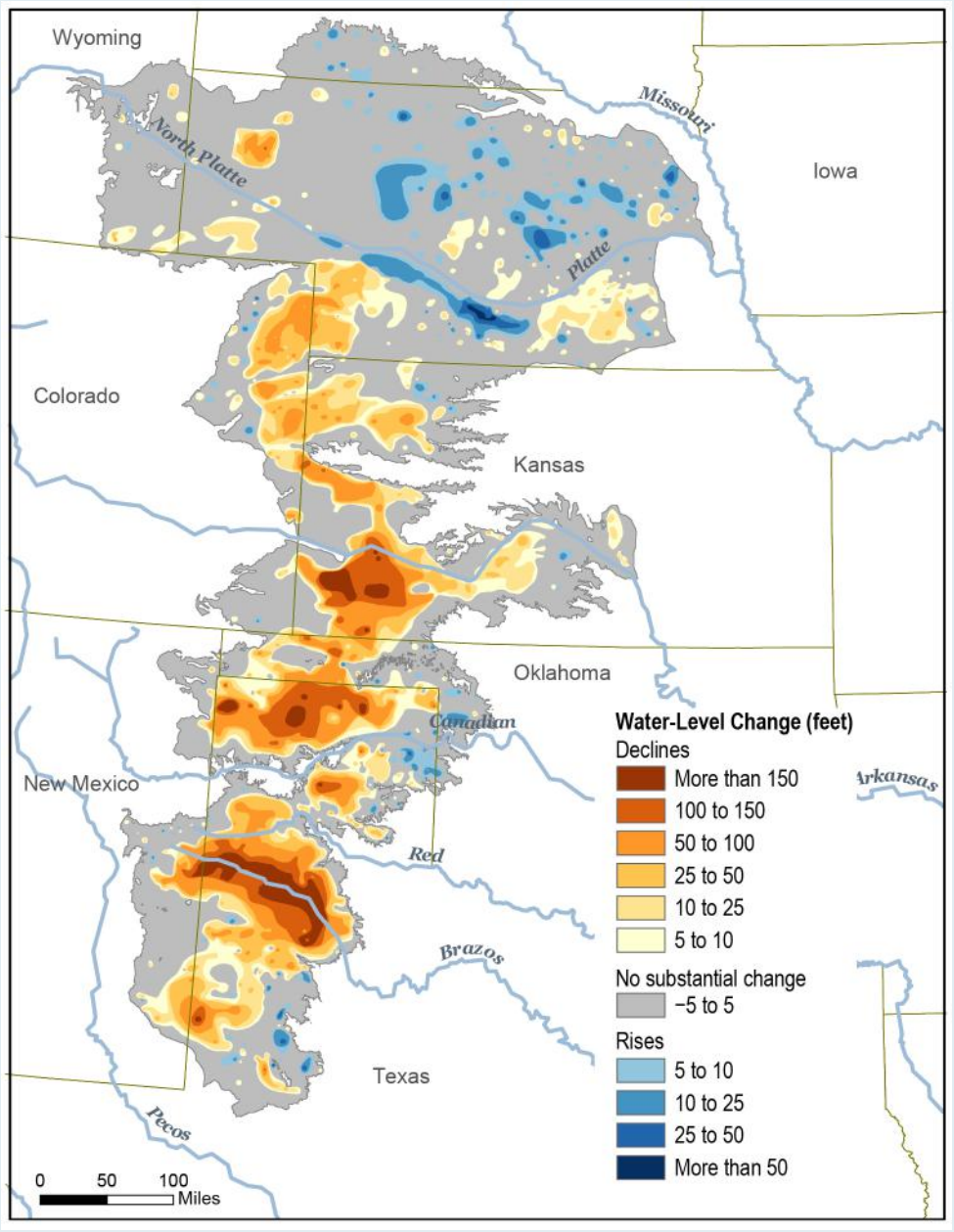


Figure 10.3: The figure shows changes in groundwater levels in the Ogallala Aquifer from predevelopment to 2015. Source: adapted from McGuire 2017.[163]

Key Message 2

Degradation of Soil and Water Resources

The degradation of critical soil and water resources will expand as extreme precipitation events increase across our agricultural landscape. Sustainable crop production is threatened by excessive runoff, leaching, and flooding, which results in soil erosion, degraded water quality in lakes and streams, and damage to rural community infrastructure. Management practices to restore soil structure and the hydrologic function of landscapes are essential for improving resilience to these challenges.

Soil erosion by water is one of the major environmental threats to sustainable crop production.[164,165] It can also adversely affect drainage networks, water quality,[166] and recreation[167]. Climate change is expected to increase the frequency of extreme precipitation events in many regions of the United States (Ch. 2: Climate). This, in turn, increases rainfall erosivity (the potential for soil to be eroded) and the sediment transport capacity of surface runoff from agricultural lands, both of which increase total soil erosion and sedimentation into receiving water bodies.[168] Therefore, increasing soil erosion rates have the potential to not only reduce agricultural productivity but also accelerate climate change effects through the loss of large stocks of carbon and nutrients stored in soil.[23,169,170]

An analysis of historical data on extreme single-day precipitation events in the United States occurring from 1910–2017 shows that the share of land area that experienced extreme precipitation regimes remained fairly steady until the 1980s but has risen significantly since then (Figure 10.4) (see also Ch. 19: Southeast, Figure 19.3).[171] This increase is expected to continue in this century. Because increased precipitation extremes elevate the risk of surface runoff, soil erosion, and loss of soil carbon, additional protective measures are needed to safeguard the progress that has been made in reducing soil erosion and water quality degradation from U.S. croplands through the implementation of grassed waterways, cover crops, conservation tillage, and waterway protection strips (Ch. 21: Midwest, KM 1).[23,172] Conservation strategies that are being implemented to reduce soil erosion and increase carbon sequestration use the estimates of expected average climate conditions derived from historical data. It is possible that these strategies could be improved by considering current and projected future climate extremes and local conditions.[23,173]

The degradation of freshwater and marine ecosystems due to sediment and nutrient loadings from agricultural landscapes is a major environmental challenge in the United States.[174,175,176,177] A strong correlation exists between extreme precipitation, high streamflow events, and large sediment and nutrient loadings entering river systems. Extreme precipitation events have been increasing across most of the United States over the past few decades; in particular, the frequency of heavy precipitation and streamflow events has increased in the central and eastern United States.[178,179,180,181] Large nutrient-rich sediment loadings, coupled with global warming, have caused increases in the duration, intensity, and extent of hypoxia (low-oxygen conditions) in coastal and freshwater systems over the past century (Ch. 21: Midwest, Case Study "Great Lakes Climate Adaptation Network").[182,183,184,185,186]

Hypoxia occurs when dissolved oxygen concentration is depleted to a certain low level below which aquatic organisms, especially

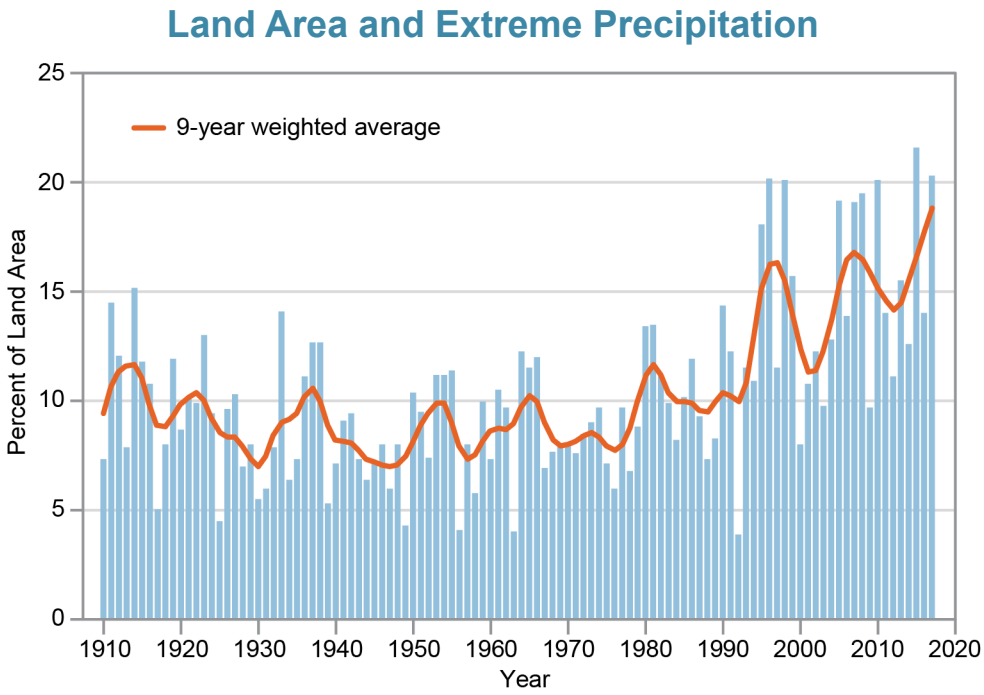


Figure 10.4: The figure shows the percent of land area in the contiguous 48 states experiencing extreme one-day precipitation events between 1910 and 2017. These extreme events pose erosion and water quality risks that have increased in recent decades. The bars represent individual years, and the orange line is a nine-year weighted average. Source: adapted from EPA 2016.[171]

immobile species such as oysters and mussels, endure severe stress or die.[187,188,189] The Chesapeake Bay,[185] the northern Gulf of Mexico,[190] and Mobile Bay[191] are common U.S. coastal locations for recurring hypoxic conditions. From 1960–2008, the incidences of hypoxia in the United States increased by a factor of 30,[192] threatening the U.S. coastal economy that in 2014, for example, generated more than $214 billion in sales and supported 1.83 million jobs.[193]

A recent study[182] found that a majority of the documented hypoxic zones around the world are in regions projected to experience an increase in temperature of 3.6°F (2˚C) by the end of century. Projections for hypoxia indicate a worsening trend, with increased frequency, intensity, and duration of hypoxic episodes.[194] The consequences of this projected trend for the environment, society, and local economies will depend on 1) a combination of climate change impacts, stemming primarily from global warming[195] and altered wind, precipitation, and ocean current patterns,[185,196,197] and 2) impacts resulting from land-use change (for example, streamflow and sediment and nutrient loadings).[182,189,194] Long-term, broad-scale efforts to reduce nutrient loads from landscapes impacted by human activity, especially agriculture, are required if water resources are to be adequately protected.[194] These efforts would require programs to monitor, study, and manage water quality problems on both regional and local scales. Numerous programs of this kind have already been established for a few major coastal water bodies, such as Lake Erie, the northern Gulf of Mexico, the Chesapeake Bay, and Long Island Sound.[198,199]

Flooding in agricultural and rural communities leads to the degradation of soil and water resources, negative impacts on human health, decreased economic activity, infrastructure damage, and environmental contamination.[200] Since the early 1900s, global sea level has risen by about 8 inches, and this has increased the

frequency, magnitude, and duration of flooding affecting agriculture and rural communities along coastal regions (Ch. 8: Coastal; Ch. 18: Northeast, KM 1 and 2). Projected climate change, including increased storm intensity and elevated global temperatures, is expected to worsen the problem. The outer range of global average sea level rise is projected to be between 1 foot and 8 feet by 2100, with a very likely range of between 1 foot and 4.3 feet (Ch. 2: Climate, KM 4 and 9),[201,202] putting U.S. coastal communities at risk, including many rural communities located along low-lying rivers in the coastal plains. Coastal erosion in the United States accounts for about $500 million in damages every year, for which the Federal Government spends an average of $150 million per year for erosion control measures.[203] Damage to coastal communities includes coastal erosion and the loss of wetlands due to flooding, coupled with high tides and sea level rise; the contamination of irrigation and drinking water due to saltwater intrusion; the loss of traditional food sources due to the loss of marine habitats and coral reefs; and the loss of agricultural lands due to rising sea levels.[204] Low-relief islands and Pacific atolls are particularly at risk to both sea level rise and increasing storm surge intensity (Ch. 8: Coastal; Ch. 15: Tribes).[205]

Key Message 3

Health Challenges to Rural Populations and Livestock

Challenges to human and livestock health are growing due to the increased frequency and intensity of high temperature extremes. Extreme heat conditions contribute to heat exhaustion, heatstroke, and heart attacks in humans. Heat stress in livestock results in large economic losses for producers. Expanded health services in rural areas, heat-tolerant livestock, and improved design of confined animal housing are all important advances to minimize these challenges.

Climate change impacts, such as extreme weather conditions, have a complex influence on human health. Specific issues are discussed in more detail in Chapter 14: Human Health. Extreme heat can cause or contribute to potentially deadly conditions such as heat exhaustion, heatstroke, and heart attacks (Ch. 18: Northeast, Figure 18.11) and reduced human productivity (Ch. 19: Southeast, Figure 19.21). In the United States, some communities of color, low-income groups, certain immigrant groups, and tribal communities are vulnerable to impacts of climate change; pregnant women, children, and older people associated with these populations are the most at risk, considering their higher likelihood of living in risk-prone areas (such as isolated rural areas and areas with poor infrastructure).[149]

Higher temperatures and consequent longer growing seasons can also affect human health by prolonging the duration of the pollen and allergy seasons.[206] Further, higher atmospheric CO_2 levels enable ragweed and other plants to produce allergenic pollen in larger quantities.[207]

Since the beginning of the 20th century, the length of the average growing season has increased by nearly two weeks in the contiguous 48 states, with larger increases in the West (2.2 days per decade) than in the East (1 day per decade). Arizona and California have recorded the most dramatic increase, while the growing season has become shorter in a few southeastern states.

Health impacts to livestock are also an important concern. Livestock and poultry account for over half of U.S. agricultural cash receipts, exceeding $182 billion in 2012.[9] One study estimated average annual losses related to heat stress for the year 2000, even with adaptation-appropriate techniques, at about $897 million, $369 million, $299 million, and $128 million for dairy, beef, swine, and poultry industries, respectively.[208] Projected increases in daily maximum temperatures and heat waves will lead to further heat stress for livestock, although the severity of consequences will vary by region. Temperatures beyond the optimal range alter the physiological functions of animals, resulting in changes in respiration rate, heart rate, blood chemistry, hormones, and metabolism; such temperatures generally result in behavioral changes as well, such as increased intake of water and reduced feed intake.[83] Heat stress also affects reproductive efficiency.[209,210] High temperatures associated with drought conditions adversely affect pasture and range conditions and reduce forage crop and grain production, thereby reducing feed availability for livestock.[54,211,212] More variable winter temperatures also cause stress to livestock and, if associated with high-moisture blizzard conditions or freezing rain and icy conditions, can result in significant livestock deaths.[213,214]

Dairy cows are particularly sensitive to heat stress, as it negatively affects their appetite, rumen fermentation (a process that converts ingested feed into energy sources for the animal), and lactation yield.[215,216] Frequent higher temperatures also lower milk quality (reduced fat, lactose, and protein percentages).[217,218] In 2010, heat stress was estimated to have lowered annual U.S. dairy production by $1.2 billion. A recent study indicates that the dairy industry expects to see production declines related to heat stress of 0.60%–1.35% for the average dairy over the next 12 years, with larger declines occurring in the Southern Great Plains and the Southeast due to increasing relative stress (assuming producing regional herd inventories remain stable; Figure 10.5).[83,218] Similar heat stress losses impact beef cow-calf, stocker, and feedlot production systems; higher temperatures result in reduced appetites and grazing/feeding activity, which subsequently reduce production efficiencies. Extreme temperature events also increase feedlot mortality.

In contrast to beef and dairy production, a much larger segment of both pork and poultry production is housed in environmentally controlled facilities that lessen the impact of temperature extremes on production efficiencies. However, these systems rely on mechanized cooling systems that are more expensive to operate as temperatures increase and are subject to extreme losses associated with the failures of cooling equipment. Traditional outdoor pork and poultry production systems will be subject to the same temperature-related issues as the beef and dairy industries. Consequently, livestock systems (such as beef and dairy cattle) that are raised outside in range environments or pen-based concentrated animal feeding operations are expected to be impacted more negatively by heat stress and climate extremes than livestock that are produced in climate-controlled facilities (such as the majority of pork and poultry).[219] As a result, feedlots and dairy production centers are expected to continue to migrate to more

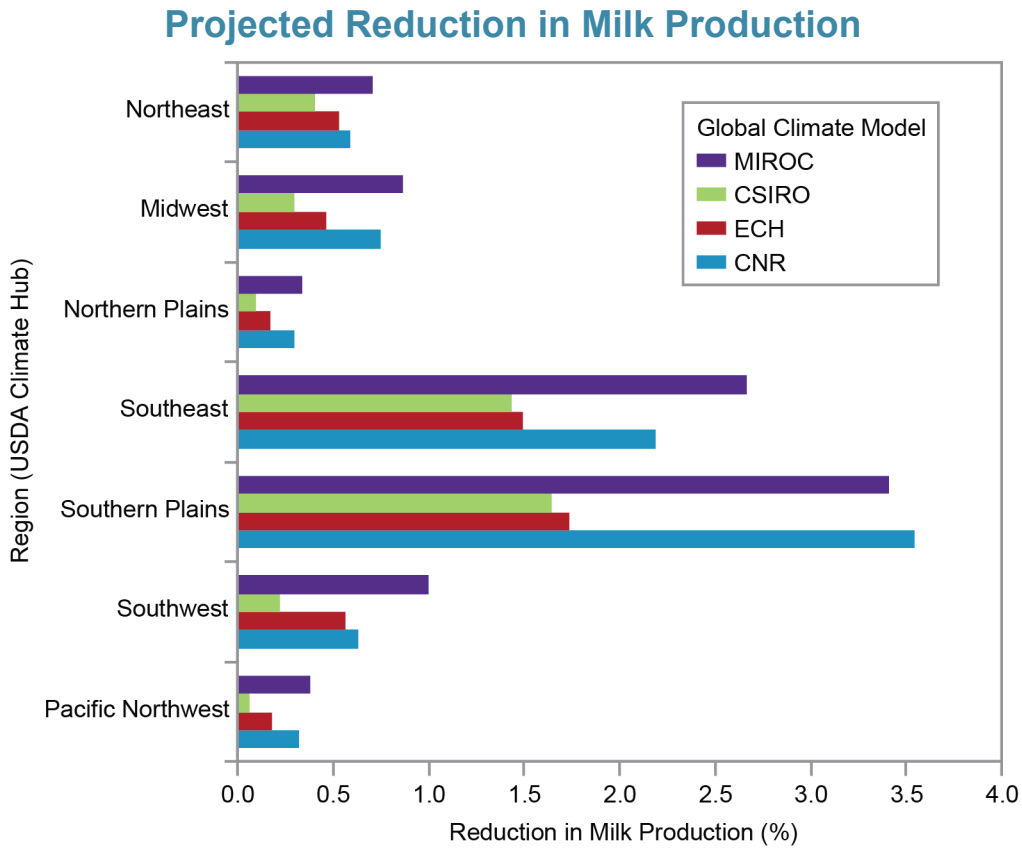


Figure 10.5: The figure shows the predicted reduction in annual milk production in 2030 compared to 2010 in climate change-induced heat stress. The regions are grouped according to USDA regional Climate Hubs (https://www.climatehubs.oce.usda.gov), and the colored bars show the four global climate models used. Source: redrawn from Key et al. 2014.[83]

temperate regions, due to heat stress, diminished water availability, and reduced crop/forage availability and quality.[54]

In the absence of migration of livestock production to more temperate climates, adaptation strategies are possible to a degree.[54] For example, as local temperatures increase, livestock can be genetically adapted to local conditions.[220] However, the physical mitigation of heat stress in livestock often requires long-term investments such as climate-controlled buildings, portable or permanent shading structures, and planted trees, as well as short-term production strategies such as altering feeds.[76,218] Studies have shown that shading in combination with fans and sprinkler or evaporative cooling technologies can mitigate the short-term effects of heat stress on animal production and reproductive efficiency.[221] Other strategies include aligning feeding and management practices with the cooler times of the day and reducing the effort required by animals to access food and water.[222]

Key Message 4

Vulnerability and Adaptive Capacity of Rural Communities

Residents in rural communities often have limited capacity to respond to climate change impacts, due to poverty and limitations in community resources. Communication, transportation, water, and sanitary infrastructure are vulnerable to disruption from climate stressors. Achieving social resilience to these challenges would require increases in local capacity to make adaptive improvements in shared community resources.

Climate change is an issue of great importance for rural communities. Rural populations are the stewards of most of the Nation's forests, watersheds, rangelands, agricultural land, and fisheries, and much of the rural economy is closely tied to its natural environment. Thus, rural residents and the lands that they manage have the potential to make important economic and conservation contributions to climate change mitigation and adaptation. However, rural residents are also highly vulnerable to climate change effects due to their economic dependence on their natural resource base, which is subject to multiple climate stressors (Ch. 19: Southeast, Figures 19.15 and 19.16; Ch. 2: Climate). Migrant workers, who provide much of the agricultural labor in some regions and some enterprises, are particularly vulnerable. Climate change has already had direct impacts on rural populations and economies (Ch. 26: Alaska, Figures 26.3 and 26.4) and will inevitably have repercussions for rural livelihoods and prosperity in the future.[223]

The ability of a rural community to adjust to climate disturbances, take advantage of economic opportunities, and cope with the consequences of change depends on a host of demographic and economic factors. Specifically, rural areas have higher percentages of people living in poverty than do urban areas, and poverty rates among historically vulnerable populations such as children, the elderly, and racial and ethnic minorities tend to be higher (Ch. 15: Tribes, Figure 15.2; Ch. 19: Southeast, Figure 19.22; Ch. 21: Midwest, KM 6, Case Study "Great Lakes Climate Adaptation Network;" KM 6; Ch. 23: S. Great Plains, KM 5).[1] The social, economic, and institutional contexts in which these vulnerable populations are embedded can further influence their individual vulnerabilities and collective capacity to communicate, cooperate, and cope with a climate disturbance event.[224] Rural communities are less likely to have local land-use regulations and building codes than urban communities, and those that do exist are more likely to be loosely enforced.[225] Lack of economic diversity, limited access to the internet, and relatively limited infrastructure, resources, and political clout further detract from the adaptive capacity of rural communities.[226,227,228] As a result, rural communities are subject to a "climate gap" defined by disproportionate and unequal impacts of climate change and extreme climate events.[229]

Vulnerability to climate change is a function of exposure, sensitivity, and adaptive capacity (Ch. 28: Adaptation). Developing the capacity to implement strategies that avoid stress or reduce system sensitivity can minimize vulnerability. Knowledge of climate change is underutilized in adaptation because procedures for incorporating climate information into decision-making have not been adequately developed.[230,231] Flexibility is a central feature of successful adaptation to climate change.[232] Adaptive capacity is highly diverse in terms of a community's ability to plan, recognize, and manage risk and then to adopt and implement

adaptation strategies.[230,233] This necessitates a range of flexible and cost-effective adaptation strategies that can address varied sensitivities and adaptive capacities (Ch. 15: Tribes, Box 15.1; Ch. 24: Northwest, Figure 24.14, Box 24.5). Innovative efforts to build capacity in rural and Indigenous communities are described in Chapter 20: U.S. Caribbean, Key Message 6 and Chapter 21: Midwest, Key Message 6.

Emerging Issues and Research Gaps

Agriculture is a highly complex system that is tightly integrated with local-to-global food systems and interlinked with rural communities that both rely on agricultural production for economic viability and support agricultural labor, input, and market requirements. Since the Third National Climate Assessment,[234] there have been significant technological advances and a renewed emphasis on conservation management and precision agriculture, especially as it relates to climate. Climate-smart agricultural initiatives (such as cover crops, specialized irrigation, and nutrient management) are being implemented to respond to or prepare for climate variability and change. In addition, genomics and plant breeding have targeted specific climate-related issues such as drought or increased ranges of pests. However, our understanding of the challenges posed by climate change is evolving, and new technologies and improved scientific understanding is warranted. Examples of these emerging issues and research gaps include the following:

- Considerable private- and public-sector research is focused on the genetic improvement of crops to enhance resilience under climate stress. However, most of the research has focused on a few major species, with minimal public resources invested in genetic improvement of specialty crops. Additionally, these efforts have focused largely on yield and much less on quality improvements that have significant nutritional and economic implications.

- Additional research would improve our understanding of the interactive effects of CO_2 concentration levels in the atmosphere, temperature, and water availability on plant physiological responses, particularly in highly dynamic field environments.

- Field-scale research has been conducted on the potential of cellulosic bioenergy crops, including grasses, fast-growing woody species, and corn residue harvest. However, the cascading effects of land-use change (from food to bioenergy crops) on rural economies, labor, and the environment remain uncertain.

- Scientific understanding of climate change impacts on beneficial and pest insects, pathogens and beneficial microorganisms, and weeds is limited, as is knowledge about the interactions of these organisms within complex agricultural landscapes.

- The Agricultural Model Intercomparison and Improvement Project (AgMIP) applies state-of-the art climate, crop/livestock, and agricultural economic models, along with stakeholder input, to coordinate multi-model regional and global assessments of climate impacts and adaptation. AgMIP is developing a rigorous process to evaluate agricultural models and thus is promoting continuous model improvement as well as supporting data sharing and the identification of adaptation technologies and policies. Currently, there is no comparable modeling framework to address animal agriculture or to evaluate the cascading effects of production on the broader food systems and food security issues.

- Agriculture has the ability to mitigate greenhouse gas emissions through carbon sequestration in the soil and perennial vegetation, through improved nutrient-use efficiency of fertilizers, and through reduced methane emissions from ruminant livestock and manure. However, the magnitude of potential mitigation, particularly of nitrous oxides from soil and soil methanogens are poorly understood. Better understanding of the soil, rhizosphere, and rumen microbiomes would improve our ability to develop mitigation strategies.

- A systems approach for research would facilitate understanding of the vulnerabilities of food systems to climate change and quantifying the costs of business as usual relative to the adoption of adaptation and mitigation strategies.

- Social science research would improve understanding of the vulnerability of rural communities, strategies to enhance adaptive capacity and resilience, and barriers to adoption of new strategies.

Acknowledgments

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Traceable Accounts

Process Description

Each regional author team organized a stakeholder engagement process to identify the highest-priority concerns, including priorities for agriculture and rural communities. Due to the heterogeneous nature of agriculture and rural communities, the national chapter leads (NCLs) and coauthor team put in place a structured process to gather and synthesize input from the regional stakeholder meetings. Where possible, one or more of the authors or the chapter lead author listened to stakeholder input during regional stakeholder listening sessions. Information about agriculture and rural communities was synthesized from the written reports from each regional engagement workshop. During the all-authors meeting on April 2–3, 2017, the NCL met with authors from each region and other national author teams to identify issues relevant to this chapter. To finalize our regional roll-up, a teleconference was scheduled with each regional author team to discuss agriculture and rural community issues. Most of the regional author teams identified issues related to agricultural productivity, with underlying topics dominated by drought, temperature, and changing seasonality. Grassland wildfire was identified as a concern in the Northern and Southern Great Plains. All regional author teams identified soil and water vulnerabilities as concerns, particularly as they relate to soil and water quality impacts and a depleting water supply, as well as reduced field operation days due to wet soils and an increased risk of soil erosion due to precipitation on frozen soil. Heat stress in rural communities and among agricultural workers was of concern in the Southeast, Southern Great Plains, Northwest, Hawai'i and Pacific Islands, U.S. Caribbean, and Northeast. Livestock health was identified as a concern in the Northeast, Midwest, U.S. Caribbean, and Southern Great Plains. Additional health-related concerns were smoke from wildfire, pesticide impacts, allergens, changing disease vectors, and mental health issues related to disasters and climate change. Issues related to the vulnerability and adaptive capacity of rural communities were identified by all regions. Discussions with the regional teams were followed by expert deliberation on the draft Key Messages by the authors and targeted consultation with additional experts. Information was then synthesized into Key Messages, which were refined based on published literature and professional judgment.

Key Message 1

Reduced Agricultural Productivity

Food and forage production will decline in regions experiencing increased frequency and duration of drought (*high confidence*). Shifting precipitation patterns, when associated with high temperatures, will intensify wildfires that reduce forage on rangelands, accelerate the depletion of water supplies for irrigation, and expand the distribution and incidence of pests and diseases for crops and livestock (*very likely, high confidence*). Modern breeding approaches and the use of novel genes from crop wild relatives are being employed to develop higher-yielding, stress-tolerant crops.

Description of evidence base

The Key Message and supporting text summarize extensive evidence documented in the U.S. Global Change Research Program's (USGCRP) *Climate Science Special Report*[84] indicating increasing drought frequency or severity in many parts of the United States, increased temperature,

and increased frost-free days. An increased probability of hot days concurrent with drought has been reported by Mueller and Seneviratne (2012),[235] Mazdiyasni and AghaKouchak (2015),[236] and Diffenbaugh et al. (2015).[107] The warming of minimum temperatures (lack of hard freezes) is contributing to expanding ranges for many insect, disease, and weed species.[237] Bebber et al. (2013)[238] report an average poleward shift of 2.7 km/year (1.68 miles/year) since 1960 of numerous pests and pathogens.

Agricultural production: Walthall et al. (2012)[38] synthesize a wide body of literature that documents the impacts of climate, including drought, on crop and livestock productivity and on the natural resources that support agricultural production. Marshall et al. 2015[97] also quantified climate change impacts on the yield of major U.S. crops as well as the reduced ability in the future to mitigate drought by irrigation. Havstad et al. (2016)[239] describe the resilience of livestock production on rangelands in the Southwest and identify adaptation management strategies needed in an increasingly arid and variable climatic environment. Liang et al. (2017)[240] found that total factor productivity (TFP) for the U.S. agriculture sector is related to regional and seasonal temperature and precipitation factors. Rosenzweig et al. (2014)[241] indicated strong negative effects of climate change on crop yields, particularly at higher levels of warming and lower latitudes. While technological improvements have outweighed the aggregate negative impacts of climate to date, projected climate change indicates that U.S. agriculture TFP could drop to pre-1980s levels by 2050. Ray et al. (2015)[242] estimate that climate accounts for about one-third of global yield variability.

Crop heat stress: Novick et al. (2016)[243] indicate that atmospheric vapor pressure deficits play a critical role in plant function and productivity and that it will become more important at higher temperatures as an independent factor, relative to available soil moisture. For instance, high temperature has been documented to decrease yields of major crops, including wheat, corn, rice, and soybean.[92,113,120,244] Multimodel simulations indicated that grain yield reductions of wheat at high temperature were associated with reduced grain number per head[120] and that yield reductions were increased with higher temperature increases across a wide range of latitudes.[241] Hatfield et al. (2017)[245] report that yield gaps for Midwest corn were negatively related to July maximum and August minimum temperatures but positively related to July–August rainfall, and that soybeans were less sensitive to projected temperature changes than corn. For corn, projected yield gaps showed a strong North–South gradient, with large gaps in southern portions of the region. Kukal and Irmak (2018)[246] reported that changes in the variability of maize, sorghum, and soybean yield patterns in the Great Plains from 1968–2013 were linked to temperature and precipitation, with irrigated crops showing low variability compared to rainfed crops. Temperature increases were detrimental to sorghum and soybean yield but not to corn during this period. Tebaldi and Lobbell (2015)[247] projected that corn would benefit from greenhouse gas mitigation to limit temperature increases throughout this century. For wheat, but less so for corn, impacts of exposure to extremely high temperatures would be partially offset by carbon dioxide fertilization effects. Tack et al. (2015)[248] report that the largest drivers of Kansas wheat yield loss over 1985–2013 were freezing temperatures in the fall and extreme heat events in the spring.[249,250] The overall effect of warming on yields was negative, even after accounting for the benefits of reduced exposure to freezing temperatures. Warming effects were partially offset by increased spring precipitation. Of concern was evidence that recently released wheat varieties are less able to resist high temperature stress than older varieties. Gammans et al. (2017)[251] found that wheat and barley yields in France were

negatively related to spring and summer temperatures. Liu et al. (2016)[252] report that with a 1.8°F (1°C) global temperature increase, global wheat yield is projected to decline between 4.1% and 6.4%, with the greatest losses in warmer wheat-producing regions. Wienhold et al. (2017)[253] identify an increase in the number of extreme temperature events (higher daytime highs or nighttime lows) as a vulnerability of Northern Great Plains crops due to increased plant stress during critical pollination and grain fill periods. Burke and Emerick (2016)[254] found that adaptation appeared to have mitigated less than half of the negative impacts of extreme heat on productivity.

Wildfire and rangelands: Margolis et al. (2017)[255] report that fire scars in tree rings for the years 1599–1899 indicate that large grassland fires in New Mexico are strongly influenced by the current year cool-season moisture, but that fires burning mid-summer to fall are also influenced by monsoon moisture. Wet conditions several years prior to the fire year, resulting in increased fuel load, are also important for spring through late-summer fires. Persistent cool-season drought lasting longer than three years may inhibit fires due to the lack of moisture to replenish surface fuels. Donovan et al. (2017)[95] reported that wildfires greater than 400 hectares increased from 33.4 ± 5.6 per year during the period 1985–1994 to 116.8 ± 28.8 wildfires per year for the period 2005–2014 and that the total area burned in the Great Plains by large wildfires increased 400%.

Water supply: Dai and Zhao (2017)[256] quantify historical trends in drought based on indices derived from the self-calibrated Palmer Drought Severity Index and the Penman–Monteith potential evapotranspiration index. For greater reliability, they compare these results with observed precipitation change patterns, streamflow, and runoff in three different periods: 1950–2012, 1955–2000, and 1980–2012. They indicate that spatially consistent patterns of drying have occurred in many parts of the Americas, that evaporation trends were slightly negative or slightly positive (exclusive of 1950–1980), and that drought has been increasingly linked to increased vapor pressure deficits since the 1980s.

Pest pressures: Integrated pest management is rapidly evolving in the face of intensifying pest challenges to crop production.[257] There is considerable capacity for genetic improvement in agricultural crops and livestock breeds, but the ultimate ability to breed increased heat and drought tolerance into germplasm while retaining desired agronomic or horticultural attributes remains uncertain.[258] The ability to breed pest-resistant varieties into a wide range of species to address rapidly evolving disease, insect, and weed species[237] is also uncertain.

Major uncertainties

Drought impacts on crop yields and forage are critical at the farm economic scale and are well documented.[38,97] However, the extent to which drought impacts larger-scale issues of food security depends on a wide range of economic and social factors that are less certain. Chavez et al. (2015)[259] lay out a framework for food security assessment that incorporates risk mitigation, risk forecast, and risk transfer instruments. There is considerable uncertainty in what is expected for the frequency and severity of future droughts.[260] However, retrospective analyses and global climate modeling of 1900–2014 drought indicators show consistent results. The applied global climate models project 50%–200% increases in agricultural drought frequency in this century, even under low forcing scenarios. There is uncertainty about the interactive effects of carbon dioxide concentration, temperature, and water availability on plant physiological responses, particularly

in highly dynamic field environments. There is uncertainty about future technological advances in agriculture and about changes in diet choices and food systems.

Description of confidence and likelihood

The USGCRP[84] determined that recent droughts and associated heat waves have reached record intensities in some regions of the United States; however, by geographic scale and duration, the 1930s Dust Bowl remains the benchmark drought and extreme heat event in the historical record since 1895 (*very high confidence*). The confidence is *high* that drought negatively impacts crop yield and quality, increases the risk of range wildfires, and accelerates the depletion of water supplies (*very likely and high confidence*).

Key Message 2

Degradation of Soil and Water Resources

The degradation of critical soil and water resources will expand as extreme precipitation events increase across our agricultural landscape (*high confidence*). Sustainable crop production is threatened by excessive runoff, leaching, and flooding, which results in soil erosion, degraded water quality in lakes and streams, and damage to rural community infrastructure (*very likely, very high confidence*). Management practices to restore soil structure and the hydrologic function of landscapes are essential for improving resilience to these challenges.

Description of evidence base

Evidence of long-term changes in precipitation is based on analyses of daily precipitation observations from the National Weather Service's Cooperative Observer Network.[261]

Groisman et al. (2012)[262] reported that for the central United States, the frequency of very heavy precipitation increased by 20% from 1979–2009 compared to 1948–1978. Slater and Villarini (2016)[263] report a significant increase in flooding frequency in the Southern Plains, California, and northern Minnesota; a smaller increase in the Southeast; and a decrease in the Northern Plains and Northwest. Mallakpour and Villarini (2015)[264] report an increasing frequency of flooding in the Midwest, primarily in summer, but find limited evidence of a change in magnitude of flood peaks.

Infrastructure: Severe local storms constituted the largest class of billion-dollar natural disasters from 1980 to 2011, followed by tropical cyclones and nontropical floods.[265] Špitalar et al. (2014)[266] evaluate flash floods from 2006 to 2012 and find that the floods with the highest human impacts, based on injuries and fatalities, are associated with small catchment areas in rural areas. Rural areas face particular challenges with road networks and connectivity.[267]

Soil and water: Soil carbon on agricultural lands is decreased due to land-use change and tillage,[268,269] resulting in decreased hydrologic function.[101] Practices that increase soil carbon have an adaptation benefit through improved soil structure and infiltration, improved water-holding capacity, and improved nutrient cycling. There are many practices that can enhance agricultural resilience through increased soil carbon sequestration.[75,268,270,271,272,273] Houghton et al. (2017)[274] identify the health effects associated with poor water quality that can be associated with nutrient transport to water bodies and subsequent eutrophication.

Major uncertainties

Floods are highly variable in space and time,[86] and their characteristics are influenced by a number of non-climate factors.[275] Groissman et al. (2012)[262] note that the lack of sub-daily data to analyze precipitation intensity means that daily data are normally used, which limits the ability to detect the most intense precipitation rates. While many practices are available to protect soil and reduce nutrient runoff from agricultural lands,[268,272] adoption rates by producers are uncertain. Additionally, there is uncertainty about the extent to which agribusiness will invest in soil improvement to mitigate risks associated with a changing climate and its effects on water, energy, and plant and animal supply chains.[276]

Description of confidence and likelihood

The evidence on increasing precipitation intensity, with the largest increases occurring in the Northeast, is high (*very likely*, *high confidence*). The increase in flooding is less certain (*likely*, *medium confidence*). The evidence of the impact of precipitation extremes on infrastructure losses, soil erosion, and contaminant transport to water bodies is well established (*very likely*, *high confidence*). Based on *medium confidence* on flooding but *high confidence* in increasing precipitation intensity and the impacts of precipitation extremes, there is *high confidence* in this Key Message.

Key Message 3

Health Challenges to Rural Populations and Livestock

Challenges to human and livestock health are growing due to the increased frequency and intensity of high temperature extremes (*very likely, high confidence*). Extreme heat conditions contribute to heat exhaustion, heatstroke, and heart attacks in humans (*very likely, high confidence).* Heat stress in livestock results in large economic losses for producers (*very likely, high confidence*). Expanded health services in rural areas, heat-tolerant livestock, and improved design of confined animal housing are all important advances to minimize these challenges.

Description of evidence base

The Key Message and supporting text summarize extensive evidence documented in the USGCRP's *Climate Science Special Report*.[84]

Humans: Houghton et al. (2017)[274] synthesize the literature that presents strong evidence of climate change impacts on human health in rural areas. Anderson et al. (2018)[278] find that heat waves pose risks to human mortality but that the risk associated with any single heat wave depends on many factors, including heat wave length, timing, and intensity. On average, heat waves increase daily mortality risk by approximately 4% in the United States,[279] but extreme heat waves present significantly higher risks. While research on heat-related morbidity has focused on urban areas, Jagai et al. (2017)[280] analyzed heat waves in Illinois over 1987–2014 and found that there were 1.16 hospitalizations per 100,000 people in the most rural, thinly populated areas, compared to 0.45 hospitalizations per 100,000 in metropolitan areas. Consequently, a 1.8°F (1°C) increase in maximum monthly temperature was associated with a 0.34 increase in hospitalization rates in rural areas compared to an increase of 0.02 per 100,000 in urbanized counties. The mean cost per hospital stay was $20,050. Fechter-Leggett et al. (2016),[281] Hess et al. (2014),[282] and Sugg et al.

(2016)[283] also report an elevated risk in rural areas for emergency room visits for heat stress. Additionally, rural areas have a high proportion of outdoor workers who are at additional risk for heat stress.[280,284,285] Merte (2017)[286] analyzed data from 1960 to 2015 for 27 European countries and found that 0.61% of all deaths were caused by extreme heat.

Major uncertainties

Humans: Much of the literature focuses on heat-related mortality in urban areas (e.g., Oleson et al. 2015, Marsha et al. 2017.[287,288]) Vulnerability and exposure in rural areas are not well understood, but Oleson et al. (2015),[287] in quantifying projected future temperature impacts, indicate that urban areas will experience more summer heat days and reduced winter cold temperature days than rural areas. Huber et al. (2017)[289] identify uncertainties in estimated impacts of death from cardiovascular diseases from a 1.8°F (1°C) increase in global temperature. Anderson et al. (2018)[278] discuss uncertainties associated with changes in the size and age of the population and the breadth of plausible socioeconomic scenarios. Jones et al. (2015)[290] identify uncertainties in the migration of population due to a changing climate and how that would impact exposure. Hallstrom et al. (2017)[291] evaluated the possible effects of future diet choices on various health indicators, many of which would have impacts on an individual's sensitivity to high temperature.

Livestock: Walthall et al. (2012)[38] synthesize a wide body of literature that documents the impacts of extreme temperature effects on livestock health and productivity. Ruminant livestock support rural livelihoods and produce high-quality food products from land that is otherwise unsuited to crop agriculture.[292,293]

Description of confidence and likelihood

Extreme temperatures are projected to increase even more than average temperatures. The temperatures of extremely cold days and extremely warm days are both projected to increase. Cold waves are projected to become less intense, while heat waves will become more intense (*very likely*, *very high confidence*).[277]

Lehner et al. (2017)[294] indicate a high likelihood and high confidence that there will be increased record-breaking summer temperatures by the end of the century. Evidence of challenges to human and livestock health due to temperature extremes is well established (*very likely*, *very high confidence*).

Key Message 4

Vulnerability and Adaptive Capacity of Rural Communities

Residents in rural communities often have limited capacity to respond to climate change impacts, due to poverty and limitations in community resources (*very likely, high confidence*). Communication, transportation, water, and sanitary infrastructure are vulnerable to disruption from climate stressors (*very likely, high confidence*). Achieving social resilience to these challenges would require increases in local capacity to make adaptive improvements in shared community resources.

Description of evidence base

A wealth of data shows that residents of rural areas generally have lower levels of education and lower wages for a given level of education compared to residents of urban areas.[295] Higher levels of poverty, particularly childhood poverty,[7] and food insecurity in rural compared to urban areas are also well documented.[49] There is also research that documents the disproportionate impacts of climate change on areas with multiple socioeconomic disadvantages, such as an increased risk of exposure to extreme heat and poor air quality, lack of access to basic necessities, and fewer job opportunities.[229]

Major uncertainties

There is uncertainty about future economic activity and employment in rural U.S. communities. However, the patterns of lower education levels, higher poverty levels, and high unemployment have been persistent and are likely to require long-term, focused efforts to reverse.[6,49,295] There are numerous federal programs (such as the USDA's regional Climate Hubs, the National Oceanic and Atmospheric Administration's Regional Integrated Sciences and Assessments program, and the U.S. Department of the Interior's Climate Adaptation Science Centers) that focus on outreach and capacity building to rural and underserved communities. Additionally, the Cooperative Extension Service and state agencies, as well as various nongovernmental organizations, provide support and services to build the adaptive capacity of individuals and communities.

Description of confidence and likelihood

Lower levels of education, poverty, limited infrastructure, and lack of access to resources will limit the adaptive capacity of individuals and communities (*very likely, high confidence*). Adaptive capacity in rural communities is being increased through federal, state, and local capacity building efforts (*likely, low to medium confidence*). However, the outreach to rural communities varies greatly in different parts of the United States.

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11 Built Environment, Urban Systems, and Cities

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11 Built Environment, Urban Systems, and Cities

Cleveland, Ohio

Key Message 1

Impacts on Urban Quality of Life

The opportunities and resources in urban areas are critically important to the health and well-being of people who work, live, and visit there. Climate change can exacerbate existing challenges to urban quality of life, including social inequality, aging and deteriorating infrastructure, and stressed ecosystems. Many cities are engaging in creative problem solving to improve quality of life while simultaneously addressing climate change impacts.

Key Message 2

Forward-Looking Design for Urban Infrastructure

Damages from extreme weather events demonstrate current urban infrastructure vulnerabilities. With its long service life, urban infrastructure must be able to endure a future climate that is different from the past. Forward-looking design informs investment in reliable infrastructure that can withstand ongoing and future climate risks.

Key Message 3

Impacts on Urban Goods and Services

Interdependent networks of infrastructure, ecosystems, and social systems provide essential urban goods and services. Damage to such networks from current weather extremes and future climate will adversely affect urban life. Coordinated local, state, and federal efforts can address these interconnected vulnerabilities.

Key Message 4

Urban Response to Climate Change

Cities across the United States are leading efforts to respond to climate change. Urban adaptation and mitigation actions can affect current and projected impacts of climate change and provide near-term benefits. Challenges to implementing these plans remain. Cities can build on local knowledge and risk management approaches, integrate social equity concerns, and join multicity networks to begin to address these challenges.

Executive Summary

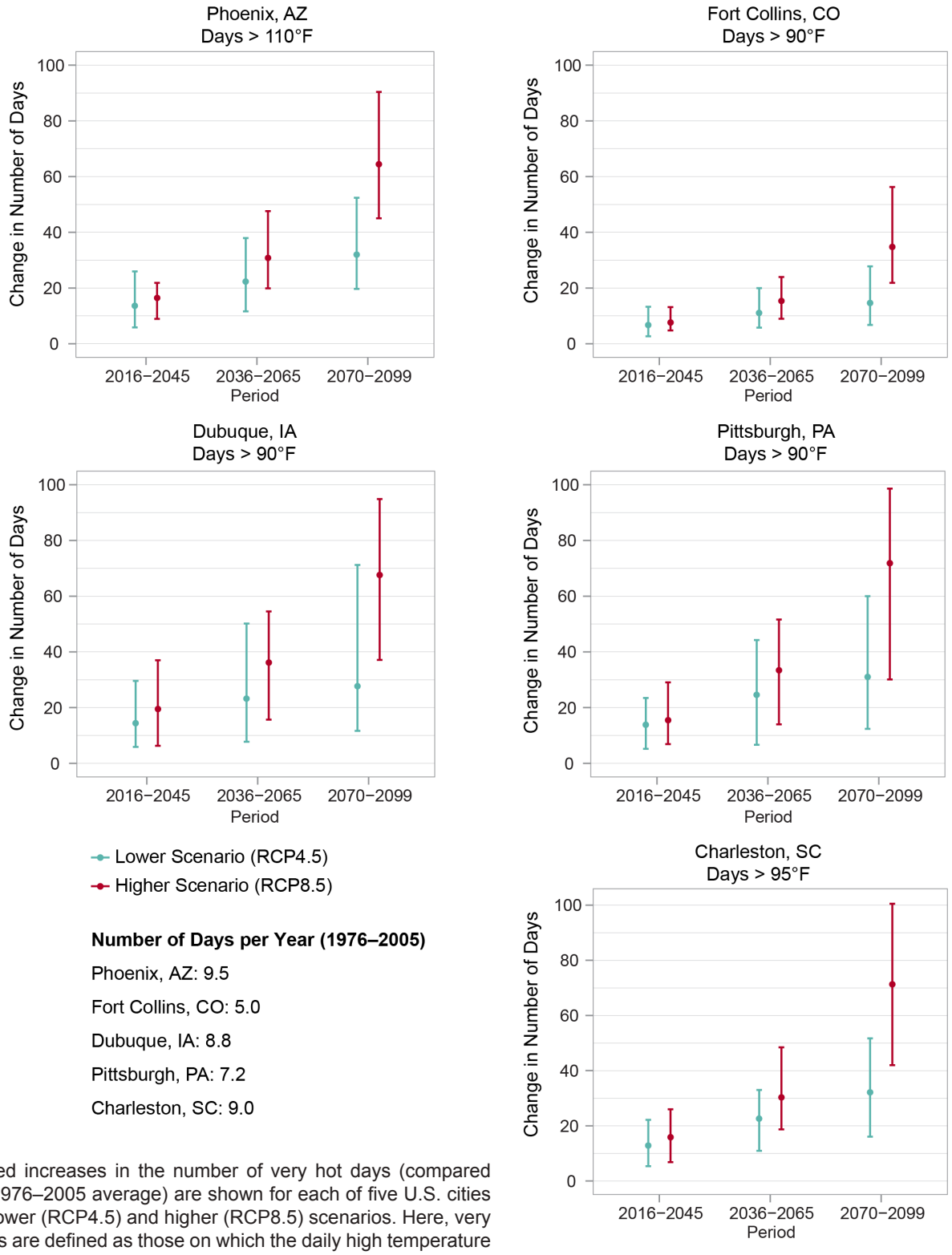
Urban areas, where the vast majority of Americans live, are engines of economic growth and contain land valued at trillions of dollars. Cities around the United States face a number of challenges to prosperity, such as social inequality, aging and deteriorating infrastructure, and stressed ecosystems. These social, infrastructure, and environmental challenges affect urban exposure and susceptibility to climate change effects.

Urban areas are already experiencing the effects of climate change. Cities differ across regions in the acute and chronic climate stressors they are exposed to and how these stressors interact with local geographic characteristics. Cities are already subject to higher surface temperatures because of the urban heat island effect, which is projected to get stronger. Recent extreme weather events reveal the vulnerability of the built environment (infrastructure such as residential and commercial buildings, transportation, communications, energy, water systems, parks, streets, and landscaping) and its importance to how people live, study, recreate, and work.

Heat waves and heavy rainfalls are expected to increase in frequency and intensity. The way city residents respond to such incidents depends on their understanding of risk, their way of life, access to resources, and the communities to which they belong. Infrastructure designed for historical climate trends is vulnerable to future weather extremes and climate change. Investing in forward-looking design can help ensure that infrastructure performs acceptably under changing climate conditions.

Urban areas are linked to local, regional, and global systems. Situations where multiple climate stressors simultaneously affect multiple city sectors, either directly or through system connections, are expected to become more common. When climate stressors affect one sector, cascading effects on other sectors increase risks to residents' health and well-being. Cities across the Nation are taking action in response to climate change. U.S. cities are at the forefront of reducing greenhouse gas emissions and many have begun adaptation planning. These actions build urban resilience to climate change.

Projected Change in the Number of Very Hot Days



Number of Days per Year (1976–2005)

Phoenix, AZ: 9.5

Fort Collins, CO: 5.0

Dubuque, IA: 8.8

Pittsburgh, PA: 7.2

Charleston, SC: 9.0

Projected increases in the number of very hot days (compared to the 1976–2005 average) are shown for each of five U.S. cities under lower (RCP4.5) and higher (RCP8.5) scenarios. Here, very hot days are defined as those on which the daily high temperature exceeds a threshold value specific to each of the five U.S. cities shown. Dots represent the modeled median (50th percentile) values, and the vertical bars show the range of values (5th to 95th percentile) from the models used in the analysis. Modeled historical values are shown for the same temperature thresholds, for the period 1976–2005, in the lower left corner of the figure. These and other U.S. cities are projected to see an increase in the number of very hot days over the rest of this century under both scenarios, affecting people, infrastructure, green spaces, and the economy. Increased air conditioning and energy demands raise utility bills and can lead to power outages and blackouts. Hot days can degrade air and water quality, which in turn can harm human health and decrease quality of life. *From Figure 11.2 (Sources: NOAA NCEI, CICS-NC, and LMI)*.

Introduction

Recent extreme weather events reveal the vulnerability of the built environment (infrastructure, such as residential and commercial buildings, transportation, communications, energy, water systems, parks, streets, and landscaping) and its importance to how people live, study, recreate, and work in cities. This chapter builds on previous assessments of urban social vulnerability and climate change impacts on urban systems.[1,2,3] It discusses recent science on urban social and ecological systems underlying vulnerability, impacts on urban quality of life and well-being, and urban adaptation. It also reviews the increase in urban adaptation activities, including investment, design, and institutional practices to manage risk. Examples of climate impacts and responses from five cities (Charleston, South Carolina; Dubuque, Iowa; Fort Collins, Colorado; Phoenix, Arizona; and Pittsburgh, Pennsylvania) illustrate the diversity of American cities and the climate risks they face.

State of the Sector

Urban areas in the United States, where the vast majority of Americans live, are engines of economic growth and contain land valued at trillions of dollars. In 2015, nearly 275 million people (about 85% of the total U.S. population) lived in metropolitan areas, and 27 million (about 8%) lived in smaller micropolitan areas.[4] Metropolitan areas accounted for approximately 91% of U.S. gross domestic product (GDP) in 2015, with over 23% coming from the five largest cities alone.[5] Urban land values are estimated at more than two times the 2006 national GDP.[6] Urbanization trends are expected to continue (Figure 11.1), and projections suggest that between 425 and 696 million people will live in metropolitan and micropolitan areas combined by 2100.[7] All of these factors affect how urban areas respond to climate change.

Cities around the United States face a number of challenges to prosperity, such as social inequality, aging and deteriorating infrastructure, and stressed ecosystems. Urban social inequality is evident in disparities in per capita income, exposure to violence and environmental hazards, and access to food, services, transportation, outdoor space, and walkable neighborhoods.[9,10,11,12] Cities are connected by networks of infrastructure, much of which is in need of repair or replacement. Failing to address aging and deteriorating infrastructure is expected to cost the U.S. GDP as much as $3.9 trillion (in 2015 dollars) by 2025.[13] Current infrastructure and building design standards do not take future climate trends into account.[14] Urbanization affects air, water, and soil quality and increases impervious surface cover (such as cement and asphalt).[15,16,17] Urban forests, open space, and waterways provide multiple benefits, but many are under stress because of land-use change, invasive species, and pollution.[18] These social, infrastructure, and environmental challenges affect urban exposure and susceptibility to climate change effects.

Urban areas, where the majority of the U.S. population lives and most consumption occurs, are the source of approximately 80% of North American human-caused greenhouse gas (GHG) emissions, despite only occupying 1%–5% of the land. Therefore, changes to urban activities can have a significant impact on national GHG emissions.[19] Land use and land-cover change contribute to radiative forcing, and infrastructure design can lock in fossil fuel dependency, so urban development patterns will continue to affect carbon sources and sinks in the future (Ch. 5: Land Changes).[19,20,21] Many cities in the United States are working to reduce their GHG emissions and can be key leverage points in mitigation efforts.

Current and Projected U.S. Population

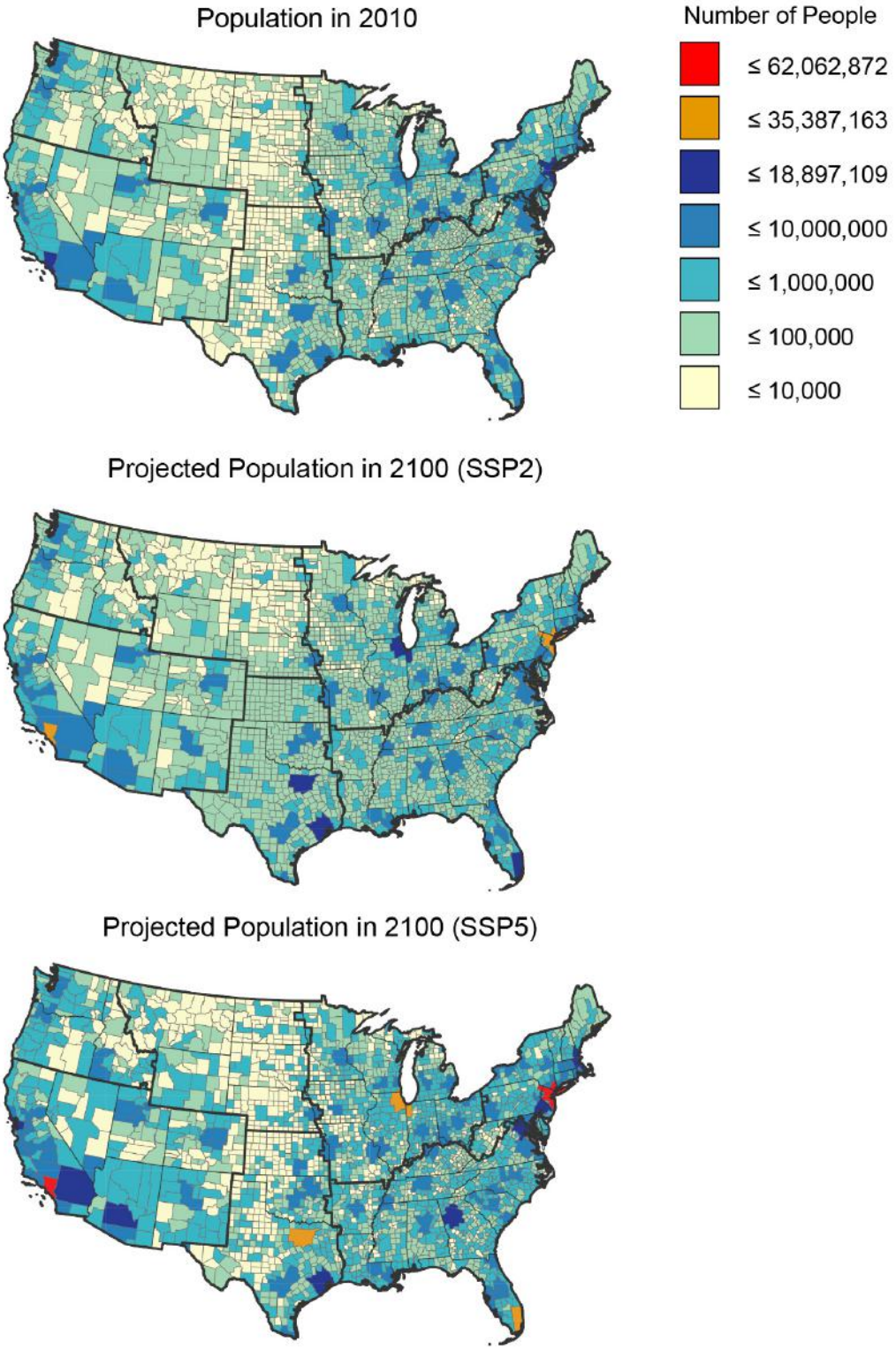


Figure 11.1: These maps show current population along with population projections by county for the year 2100. Projected populations are based on Shared Socioeconomic Pathways (SSPs)—a collection of plausible future pathways of socioeconomic development.[8] The middle map is based on demography consistent with the SSP2, which follows a middle-of-the-road path where trends do not shift markedly from historical patterns. The bottom map uses demography consistent with SSP5, which follows a more rapid technical progress and resource-intensive development path. Increasing urban populations pose challenges to planners and city managers as they seek to maintain and improve urban environments. Data are unavailable for the U.S. Caribbean, Alaska, and Hawai'i & U.S.-Affiliated Pacific Islands regions. Source: EPA

Regional Summary

Urban areas in the United States are already experiencing the effects of climate change. Across regions, U.S. cities differ in the acute and chronic climate stressors they are exposed to and how these stressors interact with local geographic characteristics.[1] In coastal areas, the built environment is subject to storm surge, high tide flooding, and saltwater intrusion (Ch. 8: Coastal, KM 1). Wildfires are on the rise in the West, lowering air quality and damaging property in cities near the wildland–urban interface (Ch. 6: Forests, KM 1; Ch. 13: Air Quality, KM 2; Ch. 14: Human Health, KM 1; Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM 2). In 2017, Los Angeles witnessed the largest wildfire in its history, with over 700 residents ordered to evacuate. The fire began during a heat wave and burned over 7,100 acres.[22] Key climate threats in the Northeast, on the other hand, are from precipitation and flooding: between 2007 and 2013, Pittsburgh experienced 11 significant flash flooding events[23,24] (Ch. 18: Northeast, KM 3). Heat waves (Figure 11.2) and heavy rainfalls (Figure 11.3) are expected to increase in frequency and intensity (Ch. 2: Climate KM 2 and 5).[25,26,27] The way city residents respond to such incidents depends on their understanding of risk, their way of life, access to resources, and the communities to which they belong.[28]

In other parts of the country, drought conditions coupled with extreme heat increase wildfire risk, and rainfall after wildfires raises flood risks.[21] In 2012 and 2013, fires destroyed hundreds of homes in the Fort Collins area of the Northern Great Plains region. In those same years, floods washed out transportation infrastructure and caused $2 billion (in 2013 dollars) in total damages.[34,35]

Despite these differences, U.S. cities experience some climate impacts in similar ways. For example, prolonged periods of high heat affect urban areas around the country.[21] Cities are already subject to higher surface temperatures because of the urban heat island (UHI) effect, which can also affect regional climate.[29] The UHI is projected to get stronger with climate change.[29] Another commonality is that most cities are subject to more than one climate stressor. Exposure to multiple climate impacts at once affects multiple urban sectors, and the results can be devastating.[30] Over a four-day period in 2015, the coastal city of Charleston in the Southeast region experienced extreme rainfall, higher sea levels, and high tide flooding. These impacts combined to cause dam failures, bridge and road closures, power outages, damages to homes and businesses, and a near shutdown of the local economy (Ch. 19: Southeast, KM 2).[31,32,33] These kinds of incidents are expected to continue as climate change brings a higher number of intense hurricanes, high tide flooding, and accelerated sea level rise (Ch. 8: Coastal, KM 1).[21]

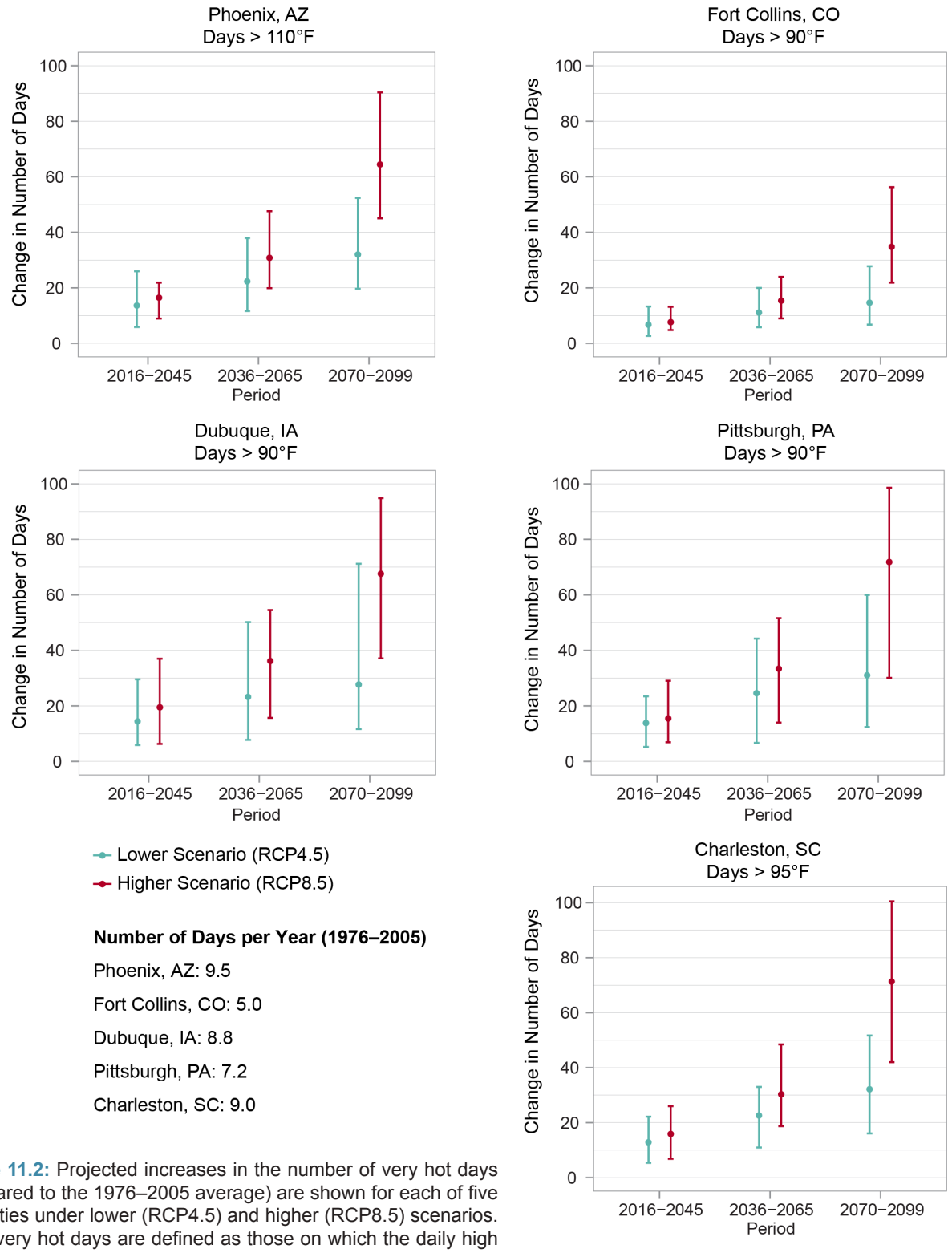


Figure 11.2: Projected increases in the number of very hot days (compared to the 1976–2005 average) are shown for each of five U.S. cities under lower (RCP4.5) and higher (RCP8.5) scenarios. Here, very hot days are defined as those on which the daily high temperature exceeds a threshold value specific to each of the five U.S. cities shown. Dots represent the modeled median (50th percentile) values, and the vertical bars show the range of values (5th to 95th percentile) from the models used in the analysis. Modeled historical values are shown for the same temperature thresholds, for the period 1976–2005, in the lower left corner of the figure. These and other U.S. cities are projected to see an increase in the number of very hot days over the rest of this century under both scenarios, affecting people, infrastructure, green spaces, and the economy. Increased air conditioning and energy demands raise utility bills and can lead to power outages and blackouts. Hot days can degrade air and water quality, which in turn can harm human health and decrease quality of life. Sources: NOAA NCEI, CICS-NC, and LMI.

Projected Change in the Number of Days with Heavy Precipitation

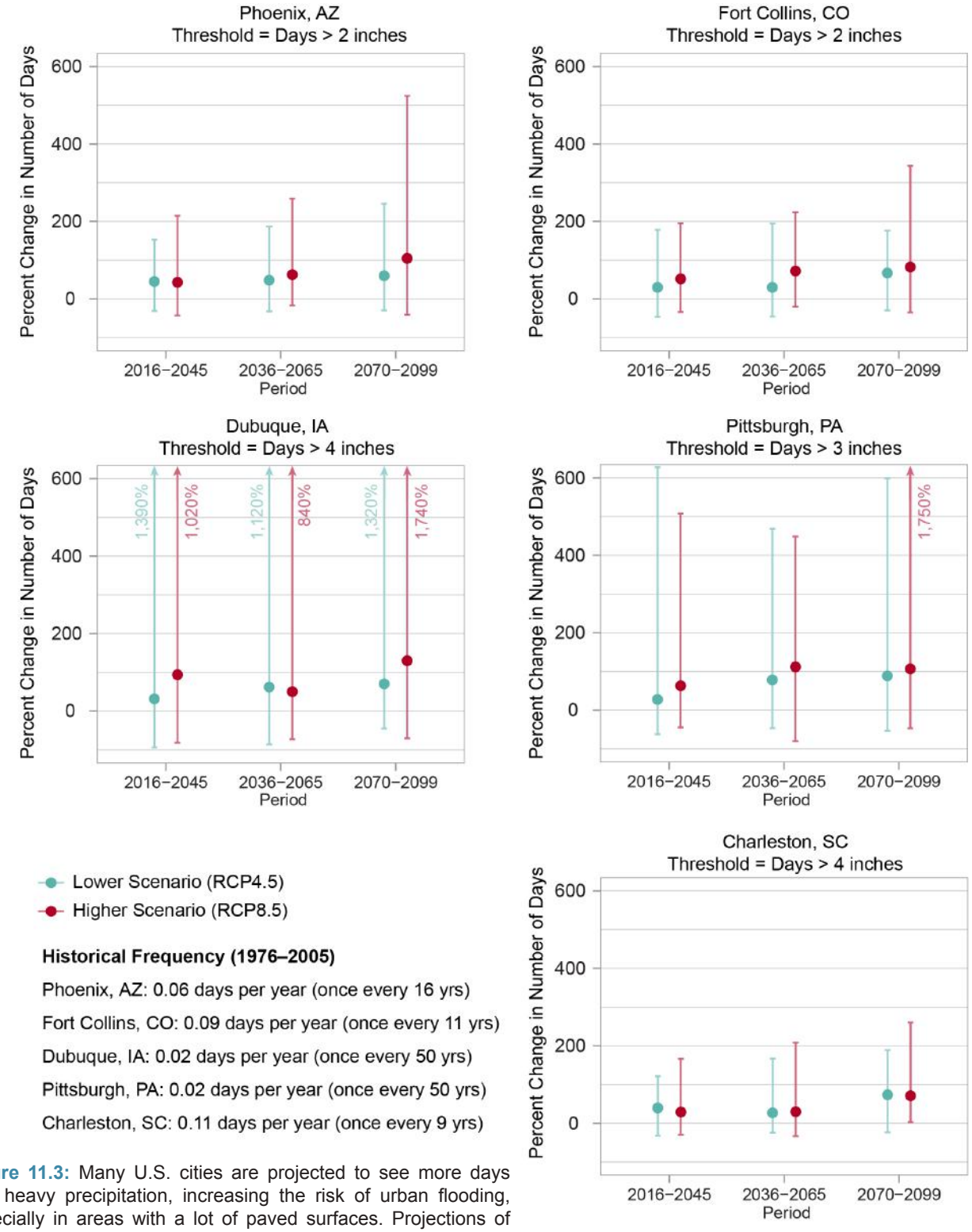


Figure 11.3: Many U.S. cities are projected to see more days with heavy precipitation, increasing the risk of urban flooding, especially in areas with a lot of paved surfaces. Projections of percent changes in the number of days with heavy precipitation (compared to the 1976–2005 average) are shown for each of five U.S. cities under lower (RCP4.5) and higher (RCP8.5) scenarios. Here, days with heavy precipitation are defined as those on which the amount of total precipitation exceeds a threshold value specific to each city. Dots represent the modeled median (50th percentile) values, and the vertical bars show the range of values (5th to 95th percentile) from the models used in the analysis. Modeled historical values are shown for the same thresholds, for the period 1976–2005, in the lower left corner of the figure. Historical values are given in terms of frequency (days per year) and return period (average number of years between events). Sources: NOAA NCEI, CICS-NC, and LMI.

Another similarity cities share is that when climate stressors affect one city sector, cascading effects on other sectors increase risks to residents' health and well-being (Ch. 17: Complex Systems). Higher temperatures can increase energy loads, which in turn can lead to structural failures in energy infrastructure, raise energy bills, and increase the occurrence of power outages (Ch. 4: Energy, KM 1). These changes strain household budgets, increase people's exposure to heat, and limit the delivery of medical and social services. For all cities, the duration of exposure to a climate stressor determines the degree of impacts. In recent years in the Southwest region, California experienced exceptional drought conditions. Urban and rural areas saw forced water reallocations and mandatory water-use reductions. Utilities had to cut back on electricity production from hydropower because of insufficient surface water flows and water in surface reservoirs (Ch. 25: Southwest, KM 1 and 5).[36,37,38]

Urban areas are linked to local, regional, and global systems.[39,40,41] For example, changes in regional food production and global trade affect local food availability.[42] Likewise, urban electricity supply often relies on far-off reservoirs, generators, and grids. Situations where multiple climate stressors simultaneously affect multiple city sectors, either directly or through system connections, are expected to become more common.[12,43,44]

Cities in all regions of the country are undertaking adaptation and mitigation actions. Several cities have climate action plans in place (see Bierbaum et al. 2013 for a review of U.S. urban adaptation plans[45]). Pittsburgh made commitments to reduce GHG emissions. Fort Collins initiated the Fort Collins ClimateWise Program. Phoenix is taking measures to reduce the UHI effect. These actions build urban resilience to climate change.

Key Message 1

Impacts on Urban Quality of Life

The opportunities and resources in urban areas are critically important to the health and well-being of people who work, live, and visit there. Climate change can exacerbate existing challenges to urban quality of life, including social inequality, aging and deteriorating infrastructure, and stressed ecosystems. Many cities are engaging in creative problem solving to improve quality of life while simultaneously addressing climate change impacts.

Cities are places where people learn, socialize, recreate, work, and live together. Quality of life for urban residents is associated with social and economic diversity, livelihood opportunities, and access to education, nature, recreation, healthcare, arts, and culture. Urban areas can foster economic prosperity and a sense of place. Yet, many cities in the United States face challenges to prosperity, including social inequality, aging and deteriorating infrastructure, and stressed ecosystems (Ch. 18: Northeast, KM 3).[13,18,46] These problems are intertwined. Climate change impacts exacerbate existing challenges to urban quality of life and adversely affect urban health and well-being.

Urban populations experiencing socioeconomic inequality or health problems have greater exposure and susceptibility to climate change.[12,47] Climate susceptibility varies by neighborhood, housing situation, age, occupation, and daily activities. People without access to housing with sufficient insulation and air conditioning (for example, renters and the homeless) have greater exposure to heat stress. Children playing outside, seniors living alone, construction workers, and athletes are also vulnerable to extreme heat (Figure 11.4).[12,48]

Threats from Extreme Heat

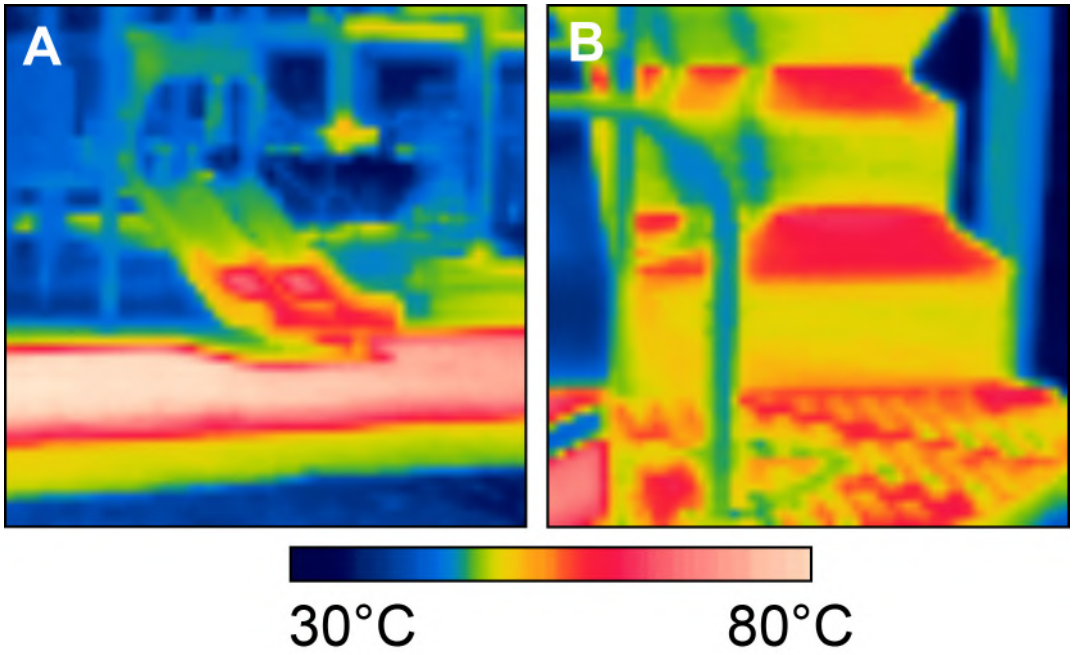


Figure 11.4: These images show surface temperatures of playground equipment in metropolitan Phoenix, Arizona. Children are particularly susceptible to high heat[12] and can be exposed through daily activities. (A) A slide and dark rubber surface in the sun (orange/red colors) are shown reaching temperatures of 71°C (160°F) and 82°C (180°F), respectively. The blue/green colors are under a shade sail. (B) Playground steps made of black powder-coated metal are shown reaching a temperature of 58°C (136°F) in the direct sunlight. Images use infrared thermography and were taken mid-day on September 15, 2014. Credit: Vanos et al. 2016.[49]

In addition to temperature extremes, climate change adversely affects urban population health through air and water quality and vector-borne diseases (Ch. 14: Human Health, KM 1). Urban residents feel economic impacts from food price volatility and the costs of insurance, energy, and water.[12,50] Climate change also threatens the integrity of personal property, ecosystems, historic landmarks, playgrounds, and cultural sites such as libraries and museums, all of which support an urban sense of place and quality of life (Ch. 24: Northwest, KM 2).[51,52,53] For example, historic landmarks in Charleston are at risk from sea level rise.[54] Urban ecosystems are further stressed by often unpredictable climate-related changes to tree species ranges, water cycles, and pest regimes.[55]

Coastal city flooding can result in forced evacuation, adversely affecting family and community stability, as well as mental and physical health (Ch. 14: Human Health, KM 1).[12] It also poses significant challenges to inland urban areas receiving these populations.[56,57] Many cities are undertaking creative problem solving to address climate change impacts and quality of life. They use approaches from urban design, sustainability, and climate justice.[58,59,60] For example, New York City's Trees for Public Health program targets street tree planting in neighborhoods of greatest need to improve the UHI effect, asthma rates, crime rates, and property values.[61]

Key Message 2

Forward-Looking Design for Urban Infrastructure

Damages from extreme weather events demonstrate current urban infrastructure vulnerabilities. With its long service life, urban infrastructure must be able to endure a future climate that is different from the past. Forward-looking design informs investment in reliable infrastructure that can withstand ongoing and future climate risks.

Urban infrastructure needs to perform reliably throughout its long service life. Infrastructure designed for historical climate trends is more vulnerable to future weather extremes and climate change. Impacts include changes in building enclosure vapor drive, energy performance, and corrosion of structures.[14,62] Above- and below-grade transportation systems are at increased risk from flooding and degradation that reduce expected service life (Ch. 12: Transportation, KM 1). Higher temperatures increase stress on cooling systems to perform as designed. High indoor temperatures reduce thermal comfort and office worker productivity, potentially requiring building closures. Over time, sea level rise and flooding are expected to destroy, or make unusable, properties and public infrastructure in many U.S. coastal cities (Ch. 8: Coastal, KM 1). Investor costs increase when infrastructure is degraded, damaged, or abandoned ahead of its anticipated useful life.[63,64]

Damages from extreme weather events demonstrate existing infrastructure vulnerabilities. Long-term, gradual risks such as sea level rise further exacerbate these vulnerabilities. Current levels of infrastructure investment in the United States are not enough to cover needed repairs and replacement.[13] Infrastructure age and disrepair make failure or interrupted service from extreme weather even more likely.[13] Heavy rainfall during Arizona's 2014 monsoon season shut down freeways and city streets in Phoenix because key pumping stations failed.[65] Climate change has already altered the likelihood and intensity of some extreme events, and there is emerging evidence that many types of extreme events will increase in intensity, duration, and frequency in the future.[27,66,67,68,69] Projecting specific changes in extreme events in particular places remains a challenge.

Costs are felt nationally as business operations, production inputs, and supply chains are affected.[70,71] Higher temperatures reduce labor productivity in construction and other outdoor industries.[12,44,72,73] Upgrades to buildings and the electrical grid are needed to handle higher temperatures.[74,75,76] Risk portfolios in the housing finance, municipal bond, and insurance industries may need to be adjusted.[44,72,77] Forward-looking design and risk management approaches support the achievement of design and investment performance goals.[78,79,80,81]

Incorporating climate projections into infrastructure design, investment and appraisal criteria, and model building codes is uncommon.[82,83,84,85,86,87,88,89] Standardized methodologies do not exist,[62,90,91,92] and the incorporation of climate projections is not required in the education or licensing of U.S. design, investment, or appraisal professionals.[80,93,94,95] Building codes and rating systems tend to be focused on current short-term, extreme weather. Investment and design standards, professional education and licensing, building codes, and zoning that use forward-looking design can protect urban assets and limit investor risk exposure.[83,96,97,98]

A handful of cities have begun to take a longer-term view toward planning.[99,100,101]

These cities have developed adaptation plans, resilience guidelines, and risk-informed frameworks. However, they do not yet have a portfolio of completed projects.[59,102] Adaptation planning is not always informed by technical analysis of changing hazards, climate vulnerability assessments, and monitoring and control systems.[79] U.S. cities can examine methods and learn from completed projects, such as those developed by Engineers Canada and UKCIP Design for Future Climate.[62,90] Managing climate risks promotes the integrity, efficiency, and safety of infrastructure to ensure reliable performance over the infrastructure's service life.[14,81]

Flash Flooding Impacts Urban Infrastructure and Well-Being

Figure 11.5: Flash flooding overwhelmed drainage systems and swamped roadways in Pittsburgh, Pennsylvania, in 2011. The flooding disrupted businesses and commutes, damaged homes, and caused four deaths. Photo credit: *Pittsburgh Post-Gazette*.

Key Message 3

Impacts on Urban Goods and Services

Interdependent networks of infrastructure, ecosystems, and social systems provide essential urban goods and services. Damage to such networks from current weather extremes and future climate will adversely affect urban life. Coordinated local, state, and federal efforts can address these interconnected vulnerabilities.

The essential goods and services that form the backbone of urban life are increasingly vulnerable to climate change. Cities are hubs of production and consumption of goods, and they are enmeshed in regional-to-global supply chains. They rely on local services and interdependent networks for telecommunications, energy, water, healthcare, transportation, and more (Ch. 4: Energy, KM 1; Ch. 3: Water, KM 1; Ch. 14: Human Health, KM 2; Ch. 12: Transportation, KM 2; Ch. 17: Complex Systems, KM 1). Gradual and abrupt climate changes disrupt the flow of these goods and services.[44] For example, the 2012 High Park Fire in Colorado had wide-reaching impacts on air and water quality. The city of Fort Collins experienced air quality that was seven times worse than the daily average (Ch. 13: Air Quality, KM 2).[103] Storms washed ash and debris into the Cache la Poudre River, polluting the city's drinking water source for residents and industries.[104] In another example, two inches of rain fell in a single hour in Pittsburgh in August 2011. Four people died in the resulting flash flood. Impervious surfaces and combined sewer systems contribute to urban flash flooding risks (Figure 11.5).[105] For similar examples of cascading impacts, see Chapter 17: Complex Systems, Box 17.1 on Hurricane Harvey and Box 17.5 on the 2003 Northeast Blackout.

Cascading Consequences of Heavy Rainfall for Urban Systems

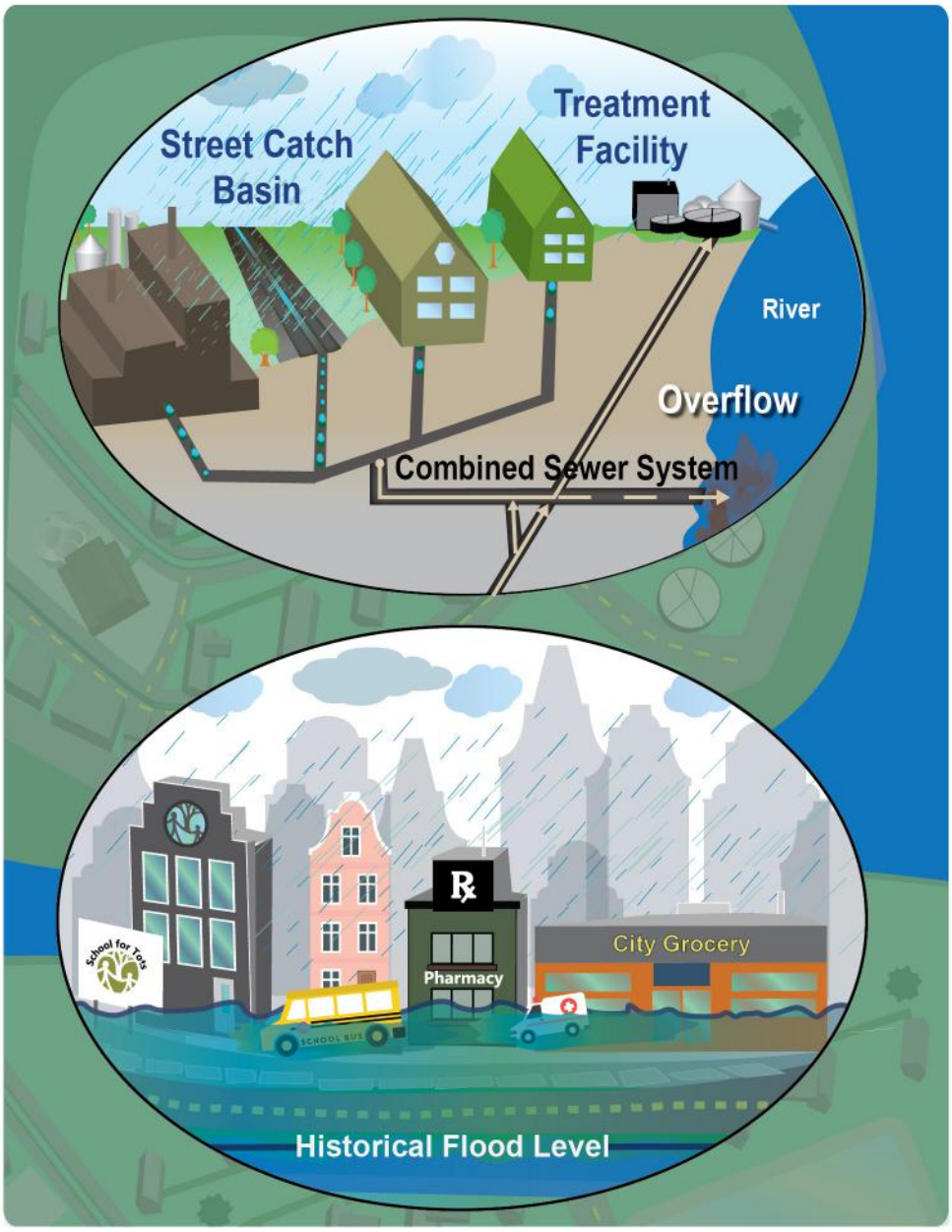


Figure 11.6: With heavy downpours increasing nationally, urban areas experience costly impacts. (top) In cities with combined sewer systems, storm water runoff flows into pipes containing sewage from homes and industrial wastewater. Intense rainfall can overwhelm the system so untreated wastewater overflows into rivers. Overflows are a water pollution concern and increase risk of exposure to waterborne diseases. (bottom) Intense rainfall can also result in localized flooding. Closed roads and disrupted mass transit prevent residents from going to work or school and first responders from reaching those in need. Home and commercial property owners may need to make costly repairs, and businesses may lose revenue. Source: EPA.

Figure 11.6 describes how heavy rainfalls, which are projected to increase with climate change, can disrupt the flow of goods and services to urban residents through increased runoff and localized flooding.

As interconnections among sectors increase, urban areas are more vulnerable to disruptions.[106] For example, energy and water systems are closely intertwined (Ch. 3: Water; Ch. 4: Energy; Ch.17: Complex Systems). Both higher water temperatures and extreme weather that causes power outages affect urban drinking

water treatment and distribution. Higher air temperatures increase urban energy demand for cooling and water demand for landscaping. Elevated water temperatures affect cooling for electricity production. Higher river temperatures during periods of low flow can require power plants to shut down or curtail power generation to stay within defined regulatory temperature limits. Higher energy loads raise the risk of power outages. Flooding can drown electrical substations. Disruptions to water and power supplies can result in problems—such as unsafe drinking water, limited access to money systems, no functioning gas stations, few available modes of transportation, no air conditioning or heating, and limited ability to communicate with others—that pose risks to urban dwellers.

Climate change also threatens food security in urban areas.[107,108] Loss of electricity from extreme weather leads to food spoilage. Transportation disruptions along the supply chain limit food mobility. Heat effects on agricultural labor impact product availability. Changes to the food supply generally lead to price volatility and food shortages, affecting household budgets and nutrition, cultural foodways, and food service profits. Urban populations who already experience food insecurity are likely to be affected the most.

Targeted coordination that addresses interconnected vulnerabilities can build urban resilience to climate change.[109,110,111] Coordination may involve municipal offices, public–private partnerships, or state and local agencies. The Charleston Resilience Network, for example, brought together public safety and health services, business organizations, and the state transportation department to discuss their performance during the region's October 2015 floods and to identify best practices to improve resilience.[112]

Key Message 4

Urban Response to Climate Change

Cities across the United States are leading efforts to respond to climate change. Urban adaptation and mitigation actions can affect current and projected impacts of climate change and provide near-term benefits. Challenges to implementing these plans remain. Cities can build on local knowledge and risk management approaches, integrate social equity concerns, and join multicity networks to begin to address these challenges.

Cities across the United States are taking action in response to climate change for a number of reasons: recent extreme weather events, available financial resources, motivated leaders, and the goal of achieving co-benefits.[113,114,115,116] One strategy being used is to mainstream adaptation and mitigation into land-use, hazard mitigation, development, and capital investment planning.[45,115,117] Municipal departments from public works to transportation play roles, as do water and energy utilities, professional societies, school boards, libraries, businesses, emergency responders, museums, healthcare systems, philanthropies, faith-based organizations, nongovernmental organizations, and residents. City governments use a variety of policy mechanisms to achieve adaptation and mitigation goals. They adopt building codes, prioritize green purchasing, enact energy conservation measures, modify zoning, and buy out properties in floodplains. Nongovernmental stakeholders take action through voluntary protocols, rating systems, and public–private partnerships, among other strategies.

U.S. cities are at the forefront of reducing greenhouse gas (GHG) emissions (Ch. 29: Mitigation, KM 1). Urban mitigation actions include acquiring

high-performance vehicle fleets and constructing energy efficient buildings. A number of cities are conducting GHG inventories to inform decisions and make commitments to reduce their emissions. Comprehensive urban carbon management involves decisions at many levels of governance.[19]

Many U.S. cities have also begun adaptation planning. A common approach is to enhance physical protection of urban assets from extreme weather. For example, protection against sea level rise and flooding can involve engineering (such as seawalls and pumps) and ecological solutions (such as wetlands and mangroves) (Ch. 8: Coastal, KM 2).[118] Green infrastructure lowers flood risk by reducing impervious surfaces and improving storm water infiltration into the ground.[72,119] Green roofs use rooftop vegetation to absorb rainfall. Urban drainage systems can be upgraded to handle increased runoff.[72] Climate-resilient building and streetscape design reduces exposure to high temperatures through tree canopy cover and cool roofs with high albedo that reflect sunlight. Ensuring that critical urban infrastructure, such as drinking water systems, continues to provide services through floods or droughts involves a combination of technology, physical protection, and outreach (Ch. 3: Water, KM 3; Ch. 19: Southeast, KM 1).[120,121,122]

Social and institutional changes are central to urban responses to climate change (Figure 11.7).[59,114] Urban development patterns reflect social, economic, and political inequities. As such,

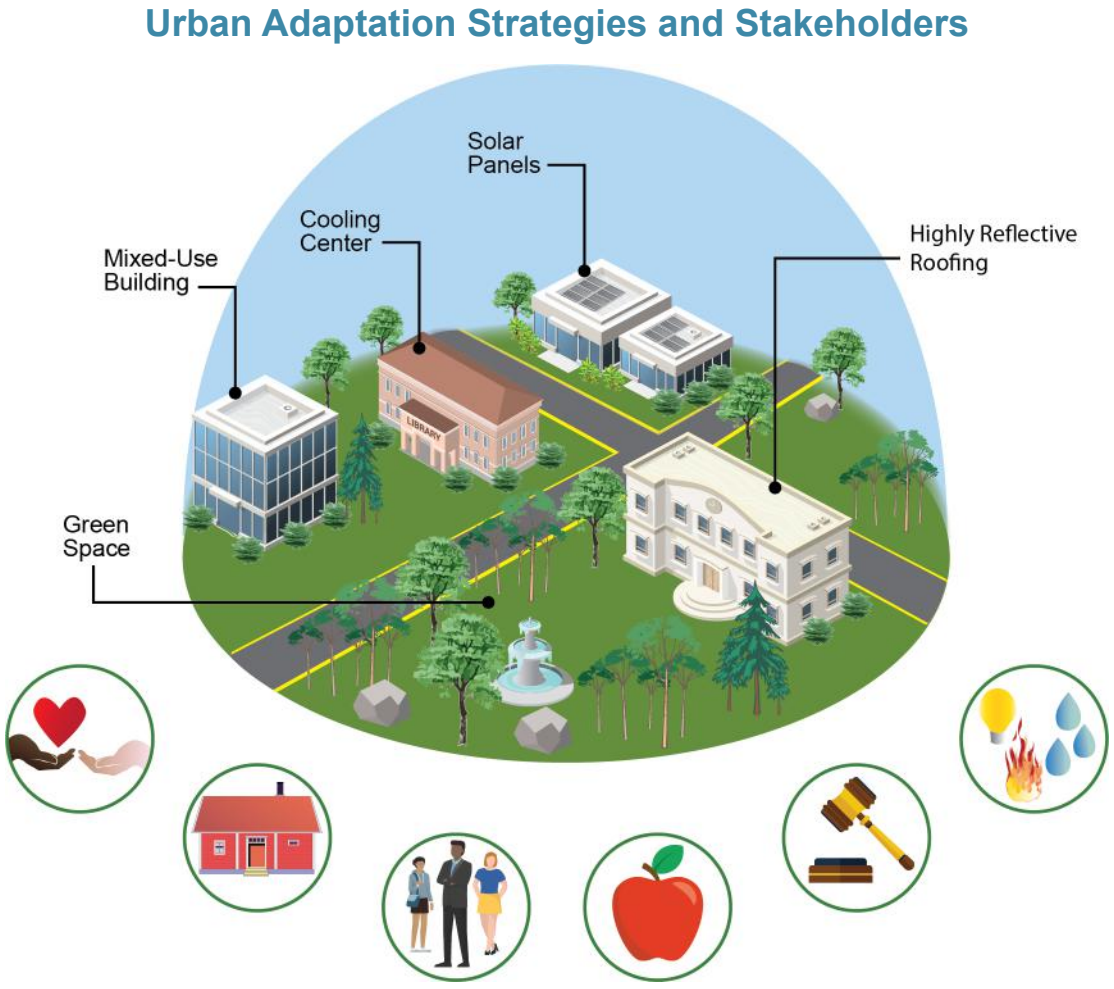


Figure 11.7: Protecting vulnerable people and places from the impacts of climate change involves infrastructure design (for example, green space and highly reflective roofing), along with social and institutional change (such as designating cooling centers). Social equity is supported by widespread participation in adaptation decision-making by non-profit organizations, local businesses, vulnerable populations, school districts, city governments, utility providers, and others. Source: EPA.

decisions about where to prioritize physical protections, install green infrastructure, locate cooling centers, or route public transportation have differential impacts on urban residents.[60,123,124,125] If urban responses do not address social inequities and listen to the voices of vulnerable populations, they can inadvertently harm low-income and minority residents.[60,123,124]

Urban actions can reduce climate change impacts on cities.[12,126,127,128,129,130] Urban adaptation plans often begin with small steps, such as improving emergency planning or requiring that development be set back from waterways (Ch. 28: Adaptation).[59,131] Not all plans address weightier concerns, tradeoffs, behaviors, and values. For example, coastal cities at risk from sea level rise may be constructing storm surge protections, but not discussing the possibility of eventual relocation or retreat (Ch. 8: Coastal, KM 3).[59,131] Increasing tree canopy and planting vegetation to manage storm water and provide cooling can increase water use, which may present difficulties for water-strapped cities.[132,133]

Urban adaptation and mitigation actions can provide near-term benefits to cities, including co-benefits to the local economy and quality of life (Ch. 29: Mitigation, KM 4).[3,19,113,134,135,136,137] Tree canopies and greenways increase thermal comfort and improve storm water management. They also enhance air quality, recreational opportunities, and property values (Figure 11.8). Wetlands serve to buffer flooding and are also a source of biodiversity and ecosystem regulation.

Urban climate change responses are often constrained by funding, technical resources,

Greenway in Dubuque, Iowa

Figure 11.8: In response to a history of flooding, Dubuque, Iowa, installed the Bee Branch Creek Greenway to control flooding and provide recreational space.[138] Photo credit: City of Dubuque, Iowa.

existing social inequities, authority, and competing priorities.[19,114,119,139,140,141] Coordinating among multiple jurisdictions and agencies is a challenge. Using scarce resources to address future risks is often a lower priority than tackling current problem areas. The absence of locally specific climate data and a standard methodology for estimating urban GHG emissions poses additional obstacles to urban responses.[19,72,114] Cities are dependent on state and national policies to modify statewide building codes, manage across landscapes and watersheds, incentivize energy efficiency, and discourage development that puts people and property in harm's way. Strong leadership and political will are central to addressing these challenges.[59,131,142] Many U.S. cities participate in networks such as the U.S. Conference of Mayors, ICLEI, the C40 Cities Climate Leadership Group (C40), and 100 Resilient Cities. Others participate in regional coalitions such as the Southeast Florida Regional Climate Change Compact. Multicity networks support development of urban climate policies and peer-to-peer learning (Ch. 28: Adaptation).[59,110,113,117,120,143] Effective urban planning to respond to climate change addresses social inequities and quality of life, uses participatory processes and risk management approaches, builds on local knowledge and values, encourages forward-looking investment, and coordinates across sectors and jurisdictions (Ch. 8: Coastal, KM 3).[59,60,115,120,124,140,142,144]

Acknowledgments

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Opening Image Credit

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Traceable Accounts

Process Description

Report authors developed this chapter through technical discussions of relevant evidence and expert deliberation and through regular teleconferences, meetings, and email exchanges. (For additional information on the overall report process, see App. 1: Process.) The author team evaluated scientific evidence from peer-reviewed literature, technical reports, and consultations with professional experts and the public via webinar and teleconferences. The scope of this chapter is urban climate change impacts, vulnerability, and response. It covers the built environment and infrastructure systems in the socioeconomic context of urban areas. This chapter updates findings from the Third National Climate Assessment and advances the understanding of previously identified urban impacts by including emerging literature on urban adaptation and emphasizing how urban social and ecological systems are related to the built environment and infrastructure. The five case-study cities were selected because they represent a geographic diversity of urban impacts from wildfire, sea level rise, heat, and inland flooding. The author team was selected based on their experiences and expertise in the urban sector. They bring a diversity of disciplinary perspectives and have a strong knowledge base for analyzing the complex ways that climate change affects the built environment, infrastructure, and urban systems.

Key Message 1

Impacts on Urban Quality of Life

The opportunities and resources in urban areas are critically important to the health and well-being of people who work, live, and visit there (*very high confidence*). Climate change can exacerbate existing challenges to urban quality of life, including social inequality, aging and deteriorating infrastructure, and stressed ecosystems (*high confidence*). Many cities are engaging in creative problem solving to improve quality of life while simultaneously addressing climate change impacts (*medium confidence*).

Description of evidence base

Urban areas provide resources and opportunities for residents' quality of life.[145,146] However, many cities face challenges to prosperity, including aging and deteriorating infrastructure,[13] social inequalities,[9,46] and lack of economic growth.[147,148] These challenges play out differently depending on a city's geographic location, economic history, urban development pattern, and governance. Studies link urban development with lower air,[15] water,[16] and soil[17] quality; altered microclimates (for example, urban heat islands);[149,150] increased risk of certain vector-borne diseases;[151] and adverse effects on biodiversity and ecosystem functioning.[152,153,154] Exposure to temperature extremes,[155] allergens,[156] and toxic substances[157] and limited access to healthy food[10,158,159] and green space[11,160,161] create environmental and social vulnerabilities for urban populations. Vulnerabilities are distributed unevenly within cities and reflect social inequalities related to differences in race, class, ethnicity, gender, health, and disability.[1] These populations of concern are at a greater risk of exposure to climate change and its impacts.[3,46,123]

Climate change combines with other trends to increase stress on the health and well-being of urban residents.[10,46,155,158] Research demonstrates that climate change can exacerbate many of the vulnerabilities described above. It raises temperatures, alters weather patterns, and increases the frequency and severity of extreme weather events, creating risks to urban ecosystems (such as urban tree cover),[162,163,164] infrastructure both above and below grade,[165,166,167] historic and cultural sites,[51,52,164,168,169,170] and residents' physical and mental health.[171,172,173,174] Coupled with climate change, urban expansion increases the risk of infectious disease[175,176] and air quality problems from wildfires.[55,177]

Metropolitan areas often have more resources than rural ones, as reflected in income per capita, employment rates, and workforce education.[178,179] Innovative urban problem solving that builds on these resources can take the form of policies and institutional collaborations,[58,180] technologies,[145,181] eco- and nature-based solutions,[182,183] public–private partnerships,[59] social network and climate justice initiatives,[60,184] "smart" cities,[106,145,181] or a combination of approaches. However, cities vary greatly in their capacity to innovate for reasons related to size, staffing, and existing resources.

Major uncertainties

It is difficult to predict future urban trends with certainty. Many factors influence the size and composition of urban populations, development patterns, social networks, cultural resources, and economic growth.[180] The degree to which climate change will exacerbate existing urban vulnerabilities depends in part on the frequency and intensity of extreme weather events,[145] which are projected with far less certainty than incremental changes in average conditions.[81] Moreover, projections are not often made at the city scale.[185] Climate change may accelerate urban tree growth, but overall effects on growing conditions depend on a variety of factors.[186] These uncertainties make it difficult to predict how climate change and other factors will intersect to affect urban quality of life. Furthermore, quality of life is difficult to measure, although some metrics are available.[187]

Urban climate vulnerability depends on local social, political, demographic, environmental, and economic characteristics.[59,110,145] Urban exposure to climate change depends on geographic factors (such as latitude, elevation, hydrology, distance from the coast).[145] Some places may be able to protect quality of life from minor climate stresses but not from extreme, though rare, events.[145] The speed and pace of innovative problem solving is difficult to predict, as is its effect on quality of life.[59]

Description of confidence and likelihood

There is *very high confidence* that the opportunities and resources available in a particular urban area influence the health and well-being of its residents. There is *high confidence* that climate change exacerbates challenges to aging and deteriorating infrastructure, degrading urban ecosystems, and urban residents' health and well-being. There is *medium confidence* that many cities are engaging in creative problem solving to address the challenges to quality of life posed by climate change. The effectiveness of this response depends on many factors (for example, intensity of extreme weather events, stakeholder collaboration, and internal and external resources available).

Key Message 2

Forward-Looking Design for Urban Infrastructure

Damages from extreme weather events demonstrate current urban infrastructure vulnerabilities (*very high confidence*). With its long service life, urban infrastructure must be able to endure a future climate that is different from the past (*very high confidence*). Forward-looking design informs investment in reliable infrastructure that can withstand ongoing and future climate risks (*high confidence*).

Description of evidence base

There is wide agreement that architects, engineers, and city planners need to consider a range of future climate conditions in urban infrastructure design to guarantee that assets perform for the duration of their expected service lives.[14,62,80,81,188,189,190,191,192] Many researchers and professionals from various industries—engineering,[80,81,193,194] water resources,[195,196] architecture, construction and building science,[62,190,197,198,199,200,201,202] transportation,[203,204,205] energy,[206] and insurance[207,208]—are actively developing or have proposed strategies to integrate climate change science and infrastructure design. The Government Accountability Office, the State of California, and a variety of professional organizations have recognized the importance of incorporating forward-looking climate information (planning for or anticipating possible future events and conditions) in design standards, building codes, zoning requirements, and professional education and training programs to protect and adapt built systems and structures. This includes the need to develop and adopt design methodologies using risk management principles for uncertainty (see Ch. 28: Adaptation, KM 3 for more discussion)[90] and the integration of climate projections, nonstationarity, and extreme value analysis to inform designs that can adapt to a range of future conditions.[8,14,80,81,90,188,190,209,210,211,212,213,214,215] Similarly, there is support for incorporating climate change risk considerations into the preparation of financial disclosures.[44,96,191,216,217] Reports from multiple sectors highlight the need for licensed design professionals, property industry professionals, and decision-makers to be aware of emerging legal liabilities linked to climate change risks.[80,95,208,218,219,220]

Numerous studies document substantial economic damages in urban areas following extreme weather events and predict an increase in damages through time as these events occur with greater frequency and intensity.[14,165,166,167,205,221] Due to underinvestment in urban infrastructure[13,222] and well-documented urban vulnerabilities to the effects of climate change and extreme weather,[80,81,223] forward-looking design strategies are critical to the future reliability of urban infrastructure.[14,80]

Major uncertainties

There are gaps in our understanding of the performance capacity of existing structures exposed to climate change stressors and of the available resources and commitment (at the state, local, tribe, and federal level) to implement forward-looking designs in investments.[192,224] The scale and speed with which climate security design principles will be integrated into infrastructure design, investments, and funding sources are difficult to predict, as are the implications for municipal bonds, solvency, and investment transparency.[77,83,96,97,98,192] There is also uncertainty regarding how

the U.S. legal system will determine the limits of professional liability for climate-related risks for licensed design professionals, attorneys, and investors.[95,218,219,220,225]

The extent to which key climate stressors will change over the design life of urban systems and structures is uncertain. It depends on the rate of global climate change as well as regional and local factors.[150,185,192] Engineering and architectural design is largely concerned with weather extremes,[80,81,190,226] which are generally projected with far less certainty than changes in average conditions.[81] Action depends on how individual decision-makers weigh the costs and benefits of implementing designs that attempt to account for future climate change. The extent to which the U.S. market is able to innovate to provide these services to the global market is unknown.

Description of confidence and likelihood

There is *very high confidence* that the integrity of urban infrastructure is and will continue to be threatened by exposure to climate change stressors (for example, more frequent and extreme precipitation events, sea level rise, and heat) and that damages from weather events demonstrate infrastructure vulnerability. Many urban areas have endured high costs from such events, and many of those costs can be attributed to infrastructure failures or damages. There is *very high confidence* that urban infrastructure will need to endure a future climate that is different from the past in order to fulfill its long service life. There is *high confidence* that investment in forward-looking design provides a foundation for reliable infrastructure that can withstand ongoing and future climate risks. How much implementing forward-looking design will reduce risks is less clear, since much depends on other factors such as changes in urban population, social inequalities, the broader economy, and rates of climate change.

Key Message 3

Impacts on Urban Goods and Services

Interdependent networks of infrastructure, ecosystems, and social systems provide essential urban goods and services (*very high confidence*). Damage to such networks from current weather extremes and future climate will adversely affect urban life (*medium confidence*). Coordinated local, state, and federal efforts can address these interconnected vulnerabilities (*medium confidence*).

Description of evidence base

Research focusing on urban areas shows that climate change has or is anticipated to have a net negative effect on transportation,[43,205,223,227] food,[44,107,108] housing,[228] the economy,[44,228,229,230,231] ecology,[3,152] public health,[2,3,12,44,231,232] energy,[43,44,233,234] water,[43,122,228,235] and sports and recreation.[2,235,236]

Researchers have modeled and documented how negative effects on one system that provides urban goods and services cascade into others that rely on it.[3,43,44,109,122,229,231,233,234] Several draw on the example of Superstorm Sandy. These effects scale up to the national economy and across to other sectors, creating longer-term hazards and vulnerabilities.[44,99,109,227] The energy–water nexus, defined as the reliance of energy and water systems on each other for functionality, is a good example of documented system interdependency.[43,234] Research indicates that direct or high-level

climate impacts on a variety of urban sectors (such as transportation, energy, drinking water, storm water) have cascading economic, socioeconomic, and public health consequences.[3,12,44,229,231]

The literature shows that coordinated resilience planning across sectors and jurisdictions to address interdependencies involves using models and plans,[3,43,108,111,227,237,238] finding effective intervention points,[109] creating system redundancy,[43,237] and motivating behavioral change. Recent reports discuss how interdependencies among energy, water, transportation, and communications services inform adaptation strategies that span sectors.[43,227]

Major uncertainties

Interconnections among urban systems have been studied less extensively than climate change effects on individual urban sectors, and there are still gaps to be filled.[239,240,241] The complexity of urban systems leads to uncertainty and modeling challenges. System models need to account for interconnections, feedback loops, and cascading effects from rural areas, among urban sectors, and within a sector. Creating a comprehensive framework to understand these connections is difficult.[239,242] There is a lack of forward-looking models of how projected climate changes will impact interdependent urban systems. Cities do not usually have the range of data needed to fully analyze system connections.[102,111] Mixed methods analysis, where professional experience and qualitative data supplement available datasets, may partially compensate for this problem.[241] Despite information gaps, urban stakeholders are beginning to address system interconnections in adaptation efforts.[59]

While it has been demonstrated that climate change affects urban systems, the extent to which climate change will affect a given urban system is difficult to predict. It depends on the unique strengths and vulnerabilities of that system as well as the regional and local climate conditions to which the system is exposed.[110,223,243] Modifying factors include spatial layout, age of infrastructure, available resources, and ongoing resilience efforts.[43,244] Similarly, critical points of intervention are unique to each urban area. Local-scale analysis of vulnerability and resilience has not been done for most U.S. cities.[102,241]

The severity of future climate impacts and cascading consequences for urban networks depends on the magnitude of global climate change.[223] Urban systems may be able to tolerate some levels of stress with only minor disruptions. Stresses of greater frequency, longer duration, or greater intensity may compromise a system's ability to function.[36,43,109,122,227] Models can reveal changes in the likelihood or frequency of occurrence for a particular type of extreme event (such as a 100-year flood), but they cannot predict when these events will occur or whether they will hit a particular city or town.[245]

Description of confidence and likelihood

There is *very high confidence* that urban areas rely on essential goods and services that are vulnerable to climate change because they are part of interdependent networks of infrastructure, ecosystems, and social systems. There is *high confidence* that extreme weather events have resulted in adverse cascading effects across urban sectors and systems, as there is documentation of a significant number of case studies of urban areas demonstrating these effects. It is projected with *medium confidence* that network damages from future climate change will disrupt many aspects of urban life, given that the complexity of urban life and the many factors affecting urban

resilience to climate change make future disruptions difficult to predict. Similarly, there is *medium confidence* that addressing interconnected vulnerabilities via coordinated efforts can build urban resilience to climate change.

Key Message 4

Urban Response to Climate Change

Cities across the United States are leading efforts to respond to climate change (*high confidence*). Urban adaptation and mitigation actions can affect current and projected impacts of climate change and provide near-term benefits (*medium confidence*). Challenges to implementing these plans remain. Cities can build on local knowledge and risk management approaches, integrate social equity concerns, and join multicity networks to begin to address these challenges (*high confidence*).

Description of evidence base

Multiple review studies have documented that cities in all parts of the United States are undertaking adaptation and mitigation actions.[45,115,246] Municipal departments, including public works, water systems, and transportation, along with public, private, and civic actors, work to assess vulnerability and reduce risk. Actions include land-use planning, protecting critical infrastructure and ecosystems, installing green infrastructure, and improving emergency preparedness and response.[45,114,115,117,247] Many cities are part of multicity networks (for example, the Great Lakes Climate Adaptation Network, ICLEI, and C40 Cities Climate Leadership Group) that provide opportunities for peer-to-peer learning, sharing best practices, and technical assistance.[59,114,117,120] Researchers have recognized the benefits of shared motivation and resource pooling across cities[59] and of incorporating local knowledge, priorities, and values into adaptation planning.[45,248] The private sector, utilities, nongovernmental organizations, libraries, museums, and civic organizations are involved with urban adaptation and mitigation.[2,45,59,115,196,249,250] Studies are beginning to analyze the social, economic, and political factors that shape whether and how cities carry out climate change response.[114,115,116,131,142]

Numerous studies have examined the ways in which adaptation actions reduce the impacts of weather extremes in urban areas. Documented benefits include reductions in urban heat risk[48,126,127,128,130,251] and flooding impacts.[118,252,253] These actions can provide additional public health and economic benefits.[59,254,255,256,257] Studies have also noted that low-regret and incremental urban adaptation are not likely to significantly reduce the impacts of projected climate change.[59,131,258] In addition, several studies discuss how urban adaptation can cause adverse consequences related to existing socioeconomic and spatial inequalities and the uneven distribution of urban climate risks.[60,123,124,125]

Major uncertainties

While urban adaptation actions can reduce the effects of extreme weather, there is uncertainty regarding the effectiveness of these actions against future climate change.[115,246] Much of this uncertainty arises from the difficulties inherent in predicting the future impacts of climate change. This uncertainty is compounded by a lack of regional and local data for many cities, by the

difficulty of evaluating the effects of climate change on local extremes,[150,251] and by the inability of knowing how climate changes intersect with other urban changes.[67,185] Moreover, there is a lack of forward-looking models and standardized monitoring strategies to test the costs, co-benefits, and effectiveness of urban response. Adaptation actions that focus solely on physical protection of urban assets are not likely to effectively address social vulnerability.[114,123] Urban adaptation effectiveness depends heavily on local characteristics. While cities do learn best practices through multicity networks, one city's strategy may not be as applicable to other cities.

Research on drivers of and challenges to urban response is in the incipient stage, with divergent results about social and political requirements for effective response.[114,116,142] Although cities are leading the way in adaptation and mitigation, many face significant barriers such as resource challenges, which will affect the rate of spread, extent, and duration of urban response.[45,145] There is little research on the effectiveness of different incentives for urban response or how to best support action in low-income communities.

Description of confidence and likelihood

There is *high confidence* that municipal governments and other institutions in many U.S. cities are planning and implementing climate change adaptation and mitigation actions. There is *high confidence* that urban adaptation and mitigation can provide additional near-term benefits, although the distribution of benefits and harms within cities is uneven. There is *medium confidence* in the effect these actions have and will have on current and future climate change impacts. If cities take only small actions, they are unlikely to fully protect urban residents from devastating impacts, particularly given projected levels of climate change. There is *high confidence* that cities face challenges in responding to climate change and that when cities build on local knowledge, use risk management approaches, explicitly address social vulnerability, and participate in multicity networks, their ability to respond to climate change is improved. The degree of improvement depends on other factors that affect urban response outcomes.

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12 Transportation

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12 Transportation

St. Louis, Missouri

Key Message 1

Transportation at Risk

A reliable, safe, and efficient U.S. transportation system is at risk from increases in heavy precipitation, coastal flooding, heat, wildfires, and other extreme events, as well as changes to average temperature. Throughout this century, climate change will continue to pose a risk to U.S. transportation infrastructure, with regional differences.

Key Message 2

Impacts to Urban and Rural Transportation

Extreme events that increasingly impact the transportation network are inducing societal and economic consequences, some of which disproportionately affect vulnerable populations. In the absence of intervention, future changes in climate will lead to increasing transportation challenges, particularly because of system complexity, aging infrastructure, and dependency across sectors.

Key Message 3

Vulnerability Assessments

Engineers, planners, and researchers in the transportation field are showing increasing interest and sophistication in understanding the risks that climate hazards pose to transportation assets and services. Transportation practitioner efforts demonstrate the connection between advanced assessment and the implementation of adaptive measures, though many communities still face challenges and barriers to action.

Executive Summary

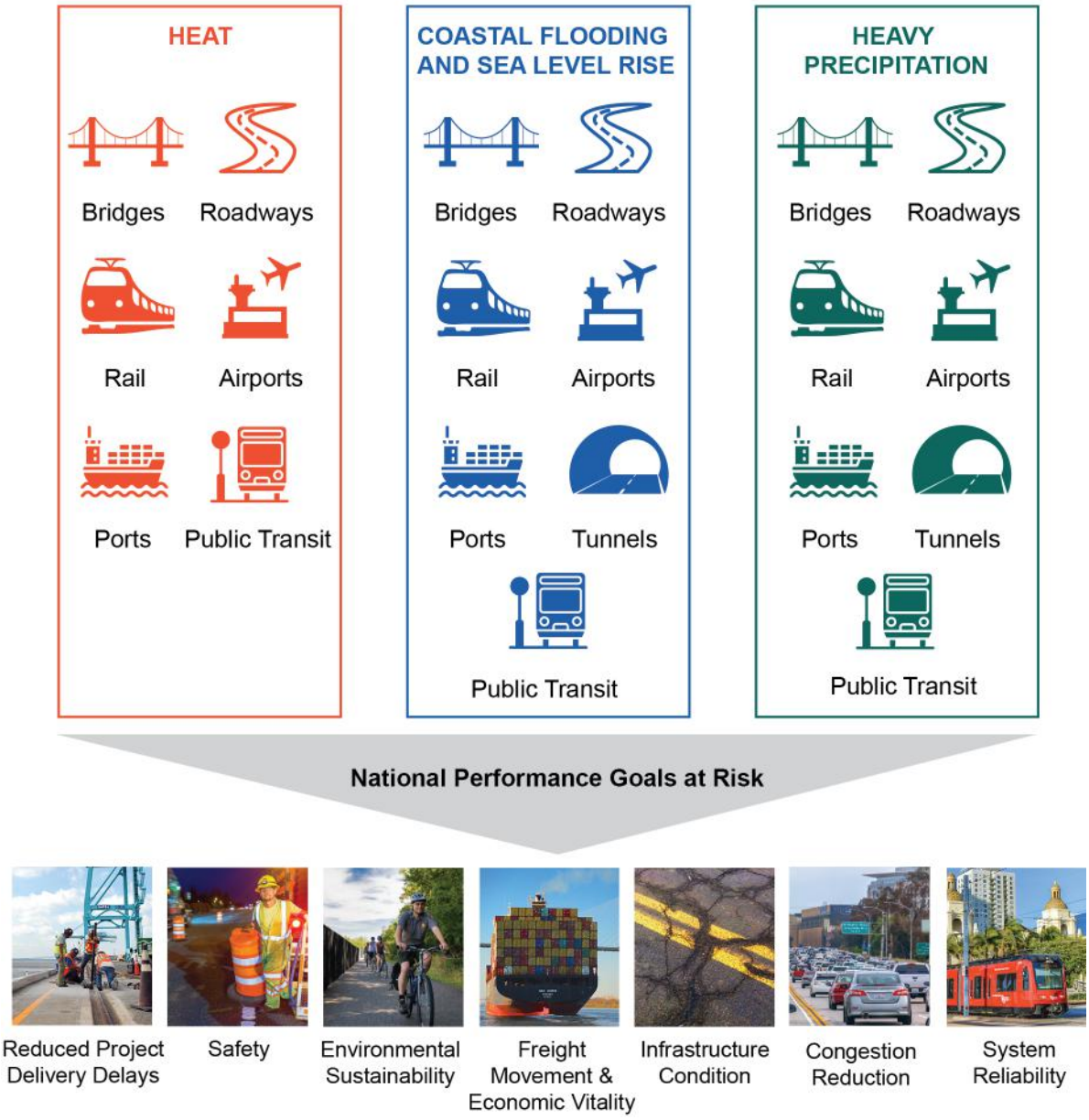
Transportation is the backbone of economic activity, connecting manufacturers with supply chains, consumers with products and tourism, and people with their workplaces, homes, and communities across both urban and rural landscapes. However, the ability of the transportation sector to perform reliably, safely, and efficiently is undermined by a changing climate. Heavy precipitation, coastal flooding, heat, wildfires, freeze–thaw cycles, and changes in average precipitation and temperature impact individual assets across all modes. These impacts threaten the performance of the entire network, with critical ramifications for economic vitality and mobility, particularly for vulnerable populations and urban infrastructure.

Sea level rise is progressively making coastal roads and bridges more vulnerable and less functional. Many coastal cities across the United States have already experienced an increase in high tide flooding that reduces the functionality of low-elevation roadways, rail, and bridges, often causing costly congestion and damage to infrastructure.[1,2] Inland transportation infrastructure is highly vulnerable to intense rainfall and flooding. In some regions, the increasing frequency and intensity of heavy precipitation events reduce transportation system efficiency[3] and increase accident risk. High temperatures can stress bridge integrity[4,5] and have caused more frequent and extended delays to passenger and freight rail systems and air traffic.[4,6]

Transportation is not only vulnerable to impacts of climate change but also contributes significantly to the causes of climate change. In 2016, the transportation sector became the top contributor to U.S. greenhouse gas emissions.[7] The transportation system is rapidly growing and evolving in response to market demand and innovation. This growth could make climate mitigation and adaptation progressively more challenging to implement and more important to achieve. However, transportation practitioners are increasingly invested in addressing climate risks, as evidenced in more numerous and diverse assessments of transportation sector vulnerabilities across the United States.

U.S. Transportation Assets and Goals at Risk

Climate Change and Notable Vulnerabilities of Transportation Assets



Heavy precipitation, coastal flooding, heat, and changes in average precipitation and temperature affect assets (such as roads and bridges) across all modes of transportation. The figure shows major climate-related hazards and the transportation assets impacted. Photos illustrate national performance goals (listed in 23 U.S.C. § 150) that are at risk due to climate-related hazards. *From Figure 12.1 (Source: USGCRP. Photo credits from left to right: JAXPORT, Meredith Fordham Hughes [CC BY-NC 2.0]; Oregon Department of Transportation [CC BY 2.0]; NPS–Mississippi National River and Recreation Area; Flickr user Tom Driggers [CC BY 2.0]; Flickr user Mike Mozart [CC BY 2.0]; Flickr user Jeff Turner [CC BY 2.0]; Flickr user William Garrett [CC BY 2.0] — see https://creativecommons.org/licenses/ for specific Creative Commons licenses).*

State of the Sector

Transportation is the backbone of economic activity, connecting manufacturers with supply chains, consumers with products and tourism, and people with their workplaces, homes, and communities across both urban and rural landscapes. In 2017, the transportation sector added over $400 billion to the U.S. gross domestic product.[9] Transportation is also an important lifeline during emergencies, which may become increasingly common under climate change scenarios (see Kossin et al. 2017[10]). In the event of a disaster, roads, airports, and harbors may serve as key modes of evacuation and often become hubs for emergency personnel and relief supplies.

The transportation sector consists of a vast, interconnected system of assets and derived services, but a changing climate undermines the system's ability to perform reliably, safely, and efficiently (Figure 12.1). Heavy precipitation, coastal flooding, heat, and changes in average precipitation and temperature impact individual assets across all modes. These impacts threaten the performance (defined by national goals listed in 23 U.S.C. § 150[8]) of the entire network,[11] with critical ramifications for safety, environmental sustainability, economic vitality and mobility, congestion, and system reliability, particularly for vulnerable populations and urban infrastructure. Fortunately, transportation professionals have made progress understanding and managing risks, though barriers persist.

Particularly as impacts compound, climate change threatens to increase the cost of maintaining infrastructure[12] approaching or beyond its design life—infrastructure that is chronically underfunded.[13] Without considering climate impacts, the American Society of Civil Engineers[14] estimates that there is already a $1.2 trillion gap in transportation infrastructure needs. The transportation network is also interdependent on other sectors, such as energy and telecommunications, which have their own climate-related vulnerabilities and existing costs.

Transportation is vulnerable to the impacts of climate change, but it also contributes significantly to the causes of climate change. In 2016, the transportation sector became the top contributor to U.S. greenhouse gas emissions.[7] Low fuel prices, which lead to more driving, coupled with increasing volumes of freight trucking, containerized shipments, and air cargo, underlie the rise in transportation emissions.[15]

The transportation system is rapidly growing and evolving in response to market demand and innovation. Passenger miles traveled on highways and on commuter rail have increased approximately 250% and 175%, respectively, since 1960,[16] and similar trends are expected to continue.[15] Projected population growth of 30% to 50% by mid-century and significant expansion of existing urban centers and surrounding communities[17] will require the transportation system to grow and will place additional demands on the existing network. Long-haul freight is expected to increase 40% by 2040,[18] while air and marine transportation will continue to grow in tandem with economic growth and international trade. This population growth and land-use change can make climate mitigation, environmental sustainability, and adaptation progressively more challenging to implement and more important to achieve.

The shifting future of transportation presents new, pressing complexities and challenges. Transportation innovations such as shared mobility (for example, car sharing, carpooling, and ride-sourcing), transit-oriented development (TOD; that is, efforts to create compact, pedestrian-oriented, mixed-use communities centered around train systems), autonomous and electrified vehicles, Next Generation air transportation technologies, megaships, and hull-cleaning robots are

emerging, but their impact on and vulnerability to climate change are still largely uncertain. For example, TOD, one of the older innovative transportation solutions, is very likely to reduce emissions and help build resilience.[19,20,21,22,23] Fuel consumption impacts of autonomous vehicles could vary greatly, depending on how they are deployed.[24] Similarly unclear is the impact that new transportation patterns, combined with deteriorating infrastructure, population growth, and land-use change, will have on the system's ability to adapt to climate change.

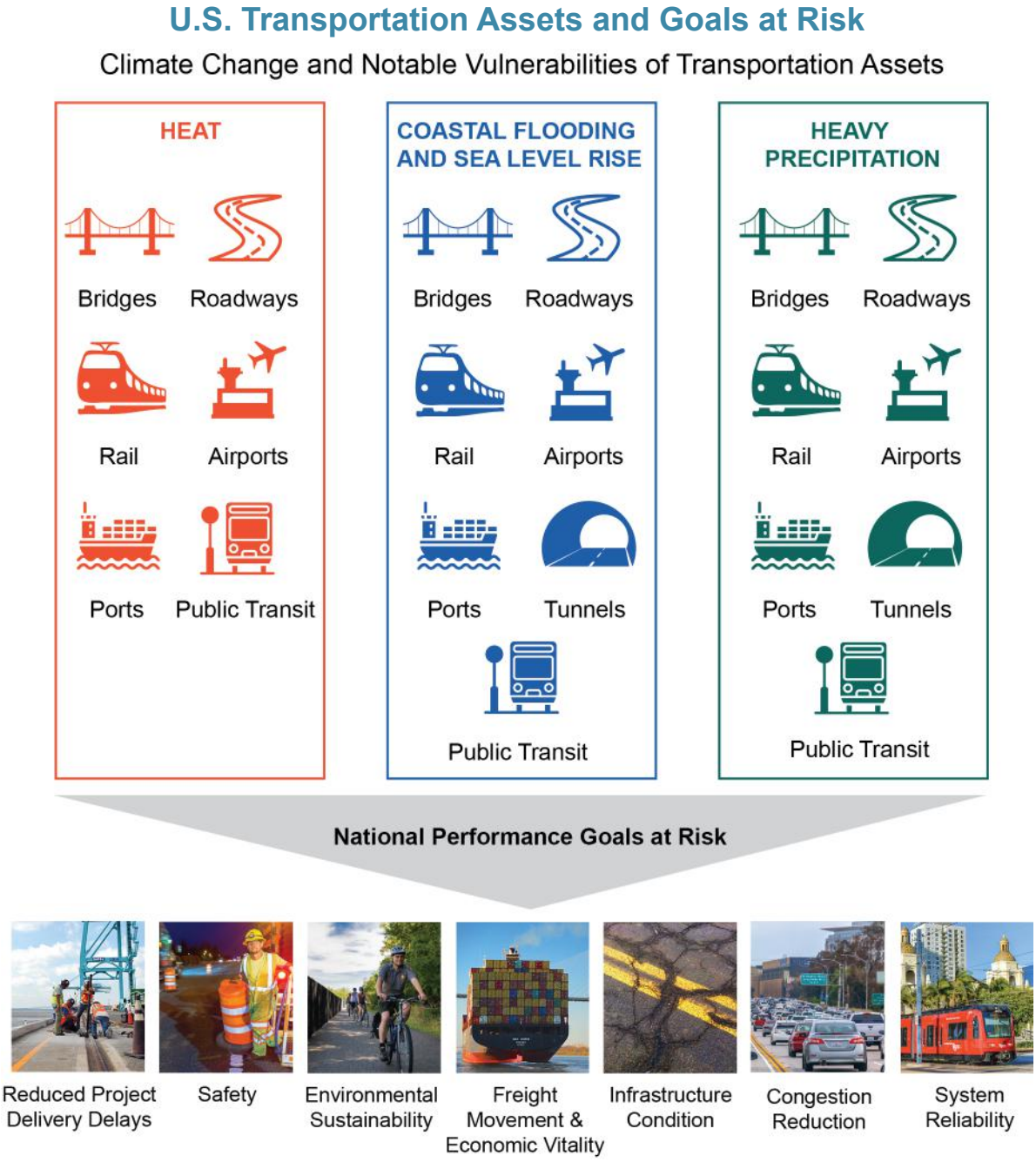


Figure 12.1: Heavy precipitation, coastal flooding, heat, and changes in average precipitation and temperature affect assets (such as roads and bridges) across all modes of transportation. The figure shows major climate-related hazards and the transportation assets impacted. Photos illustrate national performance goals (listed in 23 U.S.C. § 150[8]) that are at risk due to climate-related hazards. Source: USGCRP. Photo credits from left to right: JAXPORT, Meredith Fordham Hughes [CC BY-NC 2.0]; Oregon Department of Transportation [CC BY 2.0]; NPS–Mississippi National River and Recreation Area; Flickr user Tom Driggers [CC BY 2.0]; Flickr user Mike Mozart [CC BY 2.0]; Flickr user Jeff Turner [CC BY 2.0]; Flickr user William Garrett [CC BY 2.0].

Regional Summary

Precipitation changes are projected to vary across the country, with certainty about impacts much higher in some regions than others (Ch. 18: Northeast).[25] In the Northeast, rainfall volume and intensity have increased[25,26] and may impact transportation performance due to roadway washouts, bridge scour, and heaving or rutting due to freeze–thaw cycles, depending on site-specific conditions.[12,27,28,29] Intense precipitation at Northeast and mid-Atlantic airports has cascading effects on other airports and cargo movement networks, such as trucking and rail, due to delayed or canceled flights and stranded crews.[30,31,32] The projected increases in tropical cyclone wind speeds and rainfall intensity[33] by the end of the century indicate that shipments in Hawai'i and the Pacific Islands may be interrupted more frequently and for longer periods.[34] Storms also cause erosion and dramatic changes to island coastlines, with associated damages to roadways, harbors, and airports (Ch. 27: Hawai'i & Pacific Islands, KM 3).

In the Midwest, which has experienced an increase in riverine flooding resulting in long-term interstate freeway closures, future flooding is the main concern for transportation infrastructure (Ch. 21: Midwest, KM 5).[30] In Northeast urban regions, transportation network disruptions from high tide flooding are increasing and further stressing congested networks and storm water management systems (Ch. 18: Northeast, KM 3). Similarly, flooding in the Northwest has repeatedly blocked railways, flooded interstates, and halted freight movement, impacting access to critical services (Ch. 24: Northwest, KM 3 and 5). In the first three months of 2017, Spokane County, Washington, had already spent $2 million more than its yearly budget for road maintenance due to flooding from rapid snowmelt.[35] Flooding in the Pacific Northwest may also threaten access to recreation on federal lands, an economic driver for the region.[36]

Lack of precipitation is also a concern for the transportation network. In the past, high and low extremes in water levels in the Mississippi River and Great Lakes have limited boat traffic, affecting jobs and the ability of goods to get to domestic and international markets[37,38,39] and potentially increasing shipping costs in the future (Ch. 21: Midwest).[40]

In the Midwest, Northeast, Northern Great Plains, and Alaska, in particular, warming winters with fewer extremely cold days[41] and fewer snow and icing events[25] will likely extend the construction season, reduce winter road maintenance demand, and reduce vehicle accident risk.[42,43,44] However, when ice roads that run over a frozen water surface, such as a river or lake, start to thaw and allowable vehicle weight is therefore reduced, trucking and logging industries lose money due to limited access to road networks,[45] thus increasing transport costs (Ch. 26: Alaska, KM 5). Warming winters will also change the timing and location of freeze and thaw events, potentially increasing pavement cracking and pothole conditions in northern states.[12,45] In Alaska, near-surface permafrost thaw is responsible for severe damages to roads, airport runways, railroads, and pipelines (Ch. 26: Alaska).[46]

Climate change is projected to increase the costs of maintaining, repairing, and replacing infrastructure, with regional differences proportional to the magnitude and severity of impacts. Nationally, the total annual damages from temperature- and precipitation-related damages to paved roads are estimated at up to $20 billion under RCP8.5 in 2090 (in 2015 dollars, undiscounted, five-model average) (see the Scenario Products section of App. 3 for more on the RCPs). Inland flooding, projected to increase over the coming century, threatens approximately 2,500 to 4,600 bridges across the United States and is anticipated to result in average annual damages of $1.2 to $1.4 billion each year by 2050 (in 2015 dollars, undiscounted, five-model average).[47]

The transportation chapter of the Third National Climate Assessment highlighted Arctic warming, ports, weather-related disruptions, and adaptation strategies.[48] New research indicates that those findings are still valid concerns for the transportation sector. Some new research highlighted in this chapter includes 1) socioeconomic disparities in response to transportation vulnerabilities, 2) intermodal and cross-sector dependencies and strategies (moving toward a more holistic system as opposed to an asset-based analysis), and 3) communities' challenges, including rural communities, to identify and justify investment in transportation.

The three Key Messages discuss the physical impacts of specific climate hazards on the transportation system, economic implications of interrupted transportation, and the efforts transportation engineers, planners, and researchers are taking to understand and address current and future vulnerabilities.

Key Message 1

Transportation at Risk

A reliable, safe, and efficient U.S. transportation system is at risk from increases in heavy precipitation, coastal flooding, heat, wildfires, and other extreme events, as well as changes to average temperature. Throughout this century, climate change will continue to pose a risk to U.S. transportation infrastructure, with regional differences.

Coastal Risks

Sea level rise (SLR) is progressively making coastal roads and bridges more vulnerable and less reliable. The more than 60,000 miles of U.S. roads and bridges in coastal floodplains are clearly already vulnerable to extreme storms and hurricanes that cost billions in repairs.[49] Higher sea levels will cause more severe flooding and more damage during coastal storms and hurricanes.[50] Recent modeling shows how 1 foot of SLR combined with storm surge can result in more than 1 foot of increased storm surge.[51,52] Low-clearance bridges are particularly vulnerable to increased wave loads from storm surges that can dislodge a bridge deck.[53,54] Since the Third National Climate Assessment, new work has found that SLR has already contributed to damage of one major U.S. bridge during a hurricane: the 3-mile-long bridge carrying I-10 over Escambia Bay, in Pensacola, Florida, was severely damaged during Hurricane Ivan in 2004 (the same mechanism was observed in 2005 after Hurricane Katrina) by wave-induced loads due to a historically high storm surge.[53,55] Ports, which serve as a gateway for 99% of U.S. overseas trade,[56] are particularly vulnerable to climate impacts from extreme weather events associated with rising sea levels and tropical storm activity.[57] SLR and storm surge also threaten coastal airports.[58]

Global average sea levels are expected to continue to rise by at least several inches over the next 15 years and by 1–4 feet by 2100. This 1-to-4-foot range includes the likely projected ranges under all the RCP scenarios.[2] However, a rise of as much as 8 feet by 2100 is scientifically plausible due to possible Antarctic ice sheet instabilities.[2] Coastal infrastructure will be exposed to the effects of relative SLR, which includes vertical land motion in addition to regional variations in the distribution of the global SLR. For example, relative SLR will be higher than the global average on the East and Gulf Coasts of the United States because of the sum of these effects.[2] It is common practice for assessment and planning purposes to develop a range of scenarios of future sea levels that are consistent with these scientific estimates but not specifically based on any one. Scenarios developed by the Federal Interagency Sea Level Rise and Coastal Flood Hazard Scenarios and

Tools Task Force span the scientifically plausible range and include an Intermediate-Low scenario of 1.6 feet of global average sea level rise by 2100, an Intermediate scenario of 3.3 feet, and an Extreme scenario of 8.2 feet.[59] The relative SLR corresponding to some of these scenarios is used below to estimate increased coastal flooding delays.

Many coastal cities across the United States have experienced an increase in high tide flooding (Ch. 27: Hawai'i & Pacific Islands),[2] causing areas of permanent inundation and increased local flooding that reduce the functional performance for low-elevation roadways, rail, and bridges and often causing costly congestion and damage to infrastructure.[1,2] In Hampton Roads, Virginia, one-third of residents report flooding in their neighborhoods at least a couple of times a year, and nearly half of residents were not able to get in or out of their neighborhoods at least once within the past year due to high tide flooding.[60] On the U.S. East Coast alone, more than 7,500 miles of roadway are located in high tide flooding zones. Unmitigated, this flooding has the potential to nearly double the current 100 million vehicle-hours of delay likely by 2020 (representing an 85% increase from 2010), with a 10-fold increase by 2060 even under the Intermediate-Low SLR scenario (Figure 12.2).[61] US Route 17 in Charleston, South Carolina, currently floods more than 10 times per year and is expected to experience up to 180 floods annually by 2045, with each flood costing the city $12.5 million (in 2009 dollars, undiscounted; $13.75 million in 2015 dollars) (Ch. 19: Southeast).[2] Even if a roadway is not inundated, higher groundwater tables from SLR can impact tunnels and utility corridors and weaken roadway base materials in low-lying coastal regions.[62,63,64,65]

Precipitation and Flooding Risks

In most parts of the United States, heavy precipitation is increasing in frequency and intensity, and more severe precipitation events are anticipated in the future.[25] Inland transportation infrastructure is highly vulnerable to intense rainfall and flooding, with impacts including less reliable transportation systems[3] and increased accident risk.[66,67] Extreme precipitation events annually shut down parts of the Interstate Highway System for days or weeks due to flooding and mudslides, as happened in the first five months of 2017 in, for example, northern California (I-80) and southern California (I-880) in January, north central California (I-5) in February, Idaho (I-86) in March, and the central United States including Missouri (I-44 and I-55) in May.

Nationally, projected future increases in inland precipitation over this century will threaten approximately 2,500 to 4,600 bridges by 2050, and 5,000 to 6,000 bridges by 2090, respectively, for the lower and higher scenarios (RCP4.5 and RCP8.5).[47] Bridge failure is most common during unprecedented floods.[68] Damage due to bridge scour can result during less extreme events. This occurs when sediment around piers and abutments is washed away, compromising bridges' structural integrity.[68] Increases in rainfall intensity can accelerate bridge foundation erosion and compromise the integrity and stability of scour-critical bridges.[69]

Freight movement at major international ports can be delayed under extreme weather events that include heavy rains and/or high winds affecting crane operations and truck service.[57] Even without such disruptions, major international trade gateways, hubs, and distribution centers already experience some of the worst congestion in the country.[15]

Transportation systems that are most vulnerable to the recent observed and projected increases in precipitation intensity[25] are those where drainage is already at capacity, where projected heavy rainfall events will occur over prolonged periods, and where changing winter

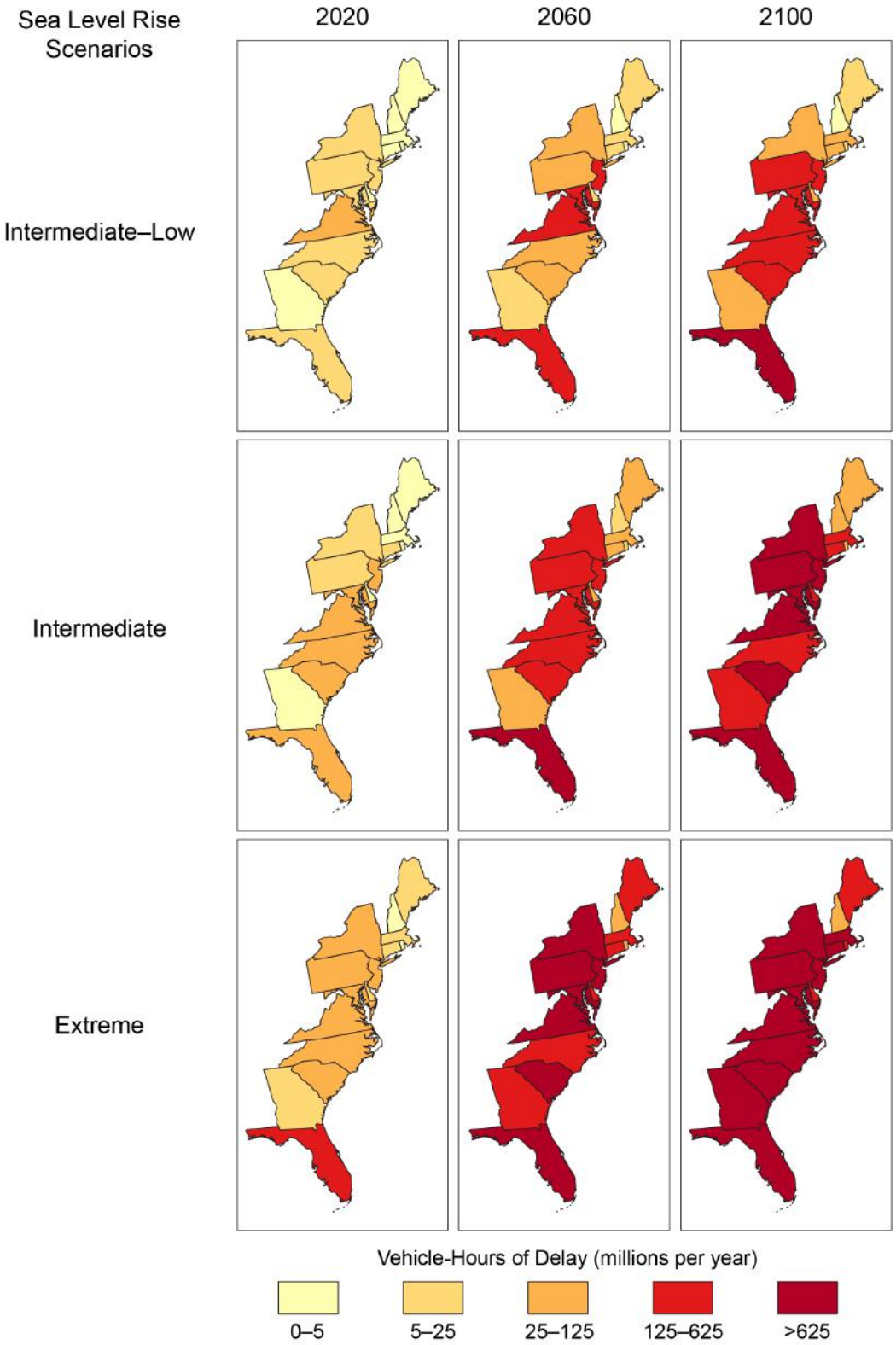


Figure 12.2: The figure shows annual vehicle-hours of delay for major roads (principal arterials, minor arterials, and major collectors) due to high tide flooding by state, year, and sea level rise scenario (from Sweet et al. 2017).[59] Years are shown using decadal average (10-year) values (that is, 2020 is 2016–2025), except 2100, which is a 5-year average (2096–2100). One vehicle-hour of delay is equivalent to one vehicle delayed for one hour. Source: Jacobs et al. 2018,[61] Figure 3, reproduced with permission of the Transportation Research Board.

precipitation increases transportation hazards from landslides and washouts.[50] In the western United States, large wildfires have increased and are likely to increase further in the future.[70] Debris flows, which consist of water, mud, and debris, are post-wildfire hazards that can escalate the vulnerability of transportation infrastructure to severe precipitation events[71] by blocking culverts and inundating roads.[72]

Rising Temperature Risks

The frequency of summer heat waves has increased since the 1960s, and average annual temperatures have increased over the past three decades; these temperature changes are projected to continue to increase in the future.[41] Across the United States, record-breaking summer temperatures and heat waves have immediate and long-term impacts on transportation. Through the urban heat island effect, heat events may become hotter and longer in cities than in the surrounding rural and suburban areas (Ch. 11: Urban).

High temperatures can stress bridge integrity.[4,5] Extreme temperatures cause frequent and extended delays to passenger and freight rail systems and air traffic when local safe operating guidelines are exceeded.[4,6] Rail tracks expand and weaken, sometimes even bend, under extreme heat.[73] Air transport is sensitive to extreme heat because hotter air makes it more difficult for airplanes to generate lift (the force required for an airplane to take flight), especially at higher elevations, requiring weight reductions and/or longer takeoff distances that may require runway extensions.[74,75]

Heat also compromises worker and public safety. Temperature extremes cause vehicles to overheat and tires to shred, while buckled roadway joints can send vehicles airborne.[76,77] Elevated temperature, combined with increased salinity and humidity, accelerates deterioration in bridges and roads constructed with concrete.[78,79] Higher ambient temperatures and extreme heat events can negatively impact pavement performance and, in turn, increase costs due to material upgrades to accommodate higher temperatures; these costs are only modestly reduced by less frequent maintenance.[12] For example, fixing pavement distress caused by a 2011 heat wave and drought cost the Texas Department of Transportation (DOT) $26 million (dollar year unspecified).[80]

Heat waves and drought require state DOTs to allocate resources to repair damaged pavement. For example, Virginia DOT has dedicated crews who quickly repair roads during extreme heat events.[81] Protocols that govern worker safety limit construction during heat waves[3,76,82] and result in lost productivity.[83] Increased cooling needed to alleviate passenger discomfort and cargo overheating[84] can cause mechanical failures and reduced service, as well as greater greenhouse gas emissions.

An additional 20–30 days per year with temperatures exceeding 90°F (32°C) are projected in most areas by mid-century under a higher scenario (RCP8.5), with increases of 40–50 days in much of the Southeast.[41] In the United States, 5.8 million miles of paved roads are susceptible to increased rutting, cracking, and buckling when sustained temperatures exceed 90°F.[85] Climate change is anticipated to increase the current $73 billion in temperature-induced railway delay costs by $25–$60 billion (in 2015 dollars, discounted at 3%).[6] Heat impacts to airports are expected to increase in the future[74] and, in some cases, are the most critical vulnerability for a region.[86]

It is possible that projected warmer conditions could have some positive effects. Milder winters will lengthen the shipping season in northern inland ports, including the Great Lakes and the Saint Lawrence Seaway.[87,88] The

reduction of snow and icing events in southern regions will likely benefit transportation safety, because snow has a significantly higher vehicle accident risk than rainfall.[66,82] Damage to bridges and roads caused by potholes and frost heaves costs hundreds of millions of dollars annually,[4] and changing winter conditions will likely alleviate expenditures in some regions but amplify expenditures in others.[12] However, thawing and freezing rain events may reduce some of the winter maintenance savings. The Alaska Department of Transportation and Public Facilities is anticipating significant challenges due to the effects of warming temperatures on roadways, and it may see increased costs in anti-icing measures in areas that previously rarely had mid-winter thawing and freezing rain.[89]

Key Message 2

Impacts to Urban and Rural Transportation

Extreme events that increasingly impact the transportation network are inducing societal and economic consequences, some of which disproportionately affect vulnerable populations. In the absence of intervention, future changes in climate will lead to increasing transportation challenges, particularly because of system complexity, aging infrastructure, and dependency across sectors.

Urban Transportation Network

The urban transportation network can be highly complex and in high demand, with populations relying on many modes of transportation across air, water, and land. U.S. urban highways tend to accommodate more than double the vehicle miles traveled compared to rural highways.[90] A high percentage of the urban population relies on public transit,[91] with greatest usage in the Northeast.[92]

The urban setting tends to amplify climate change impacts, such as flooding, on the performance of the transportation network. Combined sewer and storm sewer systems used in many cities are often not designed to withstand the capacity demand currently experienced during heavy rainfall events or rising high tides (Ch. 11: Urban). This situation is becoming increasingly problematic with more frequent localized flooding, leading to more frequent travel disruptions for commuters, travelers, and freight.[93,94] The effect is compounded in cities with older infrastructure, such as Philadelphia, Miami, Chicago, and Charleston.[94,95,96,97]

Interdependencies among transportation and other critical infrastructure sectors (such as energy) introduce the risk of significant cascading impacts on the operational capacity of the transportation urban network (Ch. 17: Complex Systems, KM 1 and 3). For example, in December 2017, Atlanta's Hartsfield–Jackson International Airport was shut down for nearly 11 hours due to a catastrophic power outage, which caused the cancellation of 1,400 flights.

In an urban environment, there is a greater chance of transportation network redundancy during an extreme weather event. For example, in the New York City metro area after Superstorm Sandy, additional bus service was able to partially compensate for flooded subway and commuter tunnels.[98,99,100] Walking also serves as an essential backstop in urban environments. For cargo, if a portion of a railway suffers damage due to a future flood event, there may be opportunities to redirect freight to highways and/or waterways.

Disruptions to the transportation network during extreme weather events can disproportionately affect low-income people, older adults, people with limited English proficiency, and other vulnerable urban populations.

These populations have fewer mobility options, reduced access to healthcare, and reduced economic ability to purchase goods and services to prepare for and recover from events.[101,102,103]

With growing suburban populations, there is increasing dependence on a variety of transportation systems. For example, in Boston, almost 130,000 people take commuter rail daily.[104] During extreme events, workers in suburban areas often cannot commute to urban offices, leading to economic losses. Evidence of this is seen from the transportation interruptions resulting from storms such as Hurricane Irene, which impacted Philadelphia and New York City, and Superstorm Sandy, which impacted the Northeast Corridor.[105] Telecommuting can mitigate some of these impacts, but a notable component of suburban areas and their economies remains dependent on a reliable transportation system.

Rural Transportation Network

The rural transportation network may lack redundancy, which increases the social and economic dependence on each road and affects agriculture, manufacturing, tourism, and more. Flood events are prolific and exemplify the dependency that rural areas have on their transportation networks. This dependence is illustrated by the 2013 flooding in Boulder, Colorado, where a 200-year flood event (an event having about a 0.5% chance of occurring in a given year) resulted in 485 miles of damaged or destroyed roadways and 1,100 landslide and hillslope failures that cut off many rural towns for weeks.[106,107] In 2016, more than 10 inches of rain caused widespread flooding throughout eastern Iowa and isolated towns along the Cedar River.[108] In 2017, Hurricane Irma entirely cut off road access to the Florida Keys.

Relative to urban areas, rural areas have fewer options for funding the maintenance and rebuilding of roads.[109] During recovery efforts, rural areas have logistical challenges that include the ability to transport the needed construction materials and a dependency on freight networks to support the population.[110] Rural communities face rebuilding challenges that often take additional time and inflict long-term economic damage to residents and local economies.[111]

Resilience Planning

Many federal, state, and municipal agencies have developed frameworks and tools to assess climate change transportation resilience, in some cases in response to legislative and policy actions. There has been an emergence of climate resilience design guidelines for new transportation infrastructure, as well as considerations of climate change in infrastructure regulations and permitting. For example, the City of New York and the Port Authority of New York and New Jersey have issued guidance that instructs project teams on how to incorporate future climate data into capital expenditures.[112,113] However, it is not only large, urban areas that are addressing potential climate impacts to transportation systems. Municipalities in states such as Wisconsin, North Carolina, Mississippi, and Tennessee are including considerations for climate vulnerability and adaptation in long-range planning.[114]

Challenges remain in the development of resilience plans. In the urban environment, issues such as predicting the potential costs of repair and identifying the rippling disruptions are required to inform the investment decision of implementing mitigation strategies.[115] Compared to urban areas, rural areas sometimes struggle to create structures and justify resilience plans, which are both cost effective and address the potential risk from climate change. As illustrated by vulnerable areas such as the

Gulf Coast, increasing storm intensity suggests the need for investments in both improved emergency management planning techniques[116] and increased transportation redundancy. Similarly, in rural mountain areas, where increased precipitation can lead to landslides, the cost of preventive actions may be difficult to justify given the uncertainty of occurrence.[117]

Key Message 3

Vulnerability Assessments

Engineers, planners, and researchers in the transportation field are showing increasing interest and sophistication in understanding the risks that climate hazards pose to transportation assets and services. Transportation practitioner efforts demonstrate the connection between advanced assessment and the implementation of adaptive measures, though many communities still face challenges and barriers to action.

Motivation for Vulnerability Assessments

Transportation practitioners are increasingly invested in addressing climate risks, as evidenced in more numerous and diverse assessments of transportation sector vulnerabilities across the United States. These assessments address the direct and indirect reactions to extreme events, funding opportunities and technical assistance and expertise, and the improved availability of climate model outputs. Federal agencies and others have made funding and tools available to evaluate asset-specific and system-wide vulnerabilities in the transportation sector.[118,119,120] For example, the Federal Highway Administration (FHWA) funded 24 pilot studies between 2010 and 2015; these pilots road-tested and advanced frameworks for conducting vulnerability assessments.[120,121,122,123] In the airport sector, the Transportation Research Board supported research and developed guidance for climate risk assessments,[124] adaptation strategies, the integration of climate risk into airport management systems, and benefit–cost analyses. A review of more than 60 vulnerability assessments published between 2012 and 2016 was conducted for this chapter. Results of this review are summarized below and depicted in Figure 12.3.

Vulnerability Assessments Synopsis

Transportation vulnerabilities to climate change can be very different from one location to another. Examining the commonality and differences among place-based vulnerability assessments provides insights into what communities feel are their greatest vulnerabilities. While early climate risk assessment relied on readily available indicators (such as location, elevation, and condition) to screen assets for exposure to climate risks, asset owners and operators have increasingly conducted more focused studies of particular assets that consider multiple climate hazards and scenarios in the context of asset-specific information, such as design lifetime. Of the 60 studies included in the online version of Figure 12.3, roadways were the most commonly assessed asset, followed by bridges and rail. Most assessments used geospatial data to identify vulnerabilities; more sophisticated assessments utilized models as well (for example, Transportation Engineering Approaches to Climate Resiliency, GC2, and the Massachusetts Department of Transportation).[125,126,127] Building on guidance from the FHWA and others,[28] some agencies engaged stakeholders to ground-truth and/or fortify their results.[128]

Most studies focus on multiple climate stressors, including both chronic issues (such as sea level rise) and extreme events (such as flooding, storm surge, and extreme heat). Sea level rise and flooding are the most commonly assessed individual stressors. Although combined risks are rarely assessed, sea level rise and storm surge are sometimes considered together. The majority of

Transportation Vulnerability and Risk Assessments

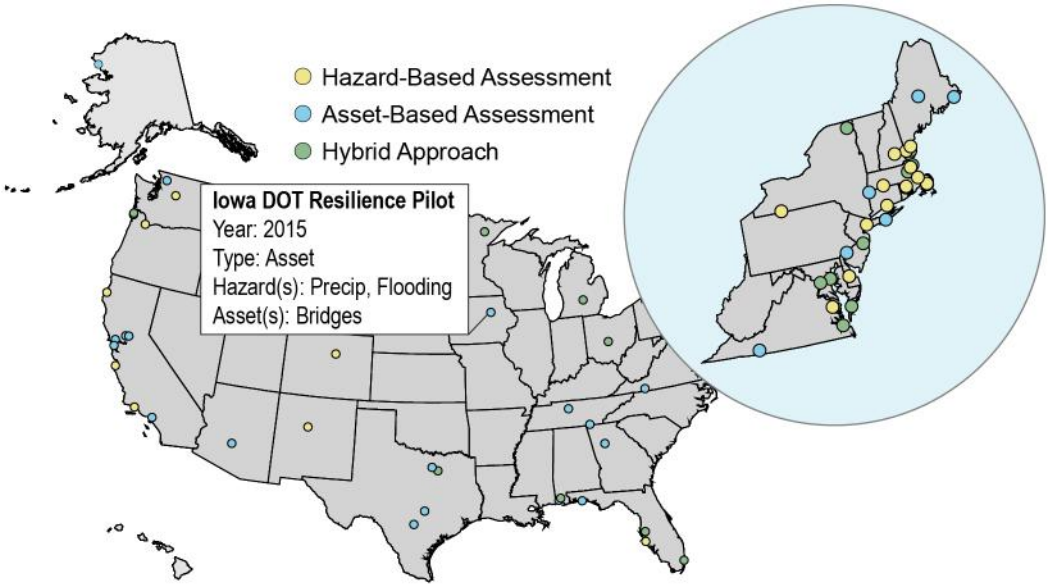


Figure 12.3: This figure shows transportation vulnerability and/or risk assessments from 2012 to 2016 by location. Cumulatively, these vulnerability assessments elucidate national-scale vulnerabilities and progress. Data for the U.S. Caribbean region were not available. See the online version of this map at http://nca2018.globalchange.gov/chapter/12#fig-12-3 to access the complete set of vulnerability and risk assessments. Sources: ICF and U.S. Department of Transportation.

assessments consider only asset-specific vulnerabilities and not transportation system-wide vulnerabilities or vulnerabilities influencing or arising from interdependencies with other sectors (such as water or energy).

The few studies that quantify the costs and benefits from adaptation primarily focus on single assets, rather than the system, and do not quantify both the direct and indirect (such as labor costs) economic costs of transportation system disruptions. The U.S. DOT Hampton Roads Climate Impact Quantification Initiative, currently underway, seeks to demonstrate a replicable approach to considering these costs.[129]

Implementation of Resilience Measures

Proactive implementation of resilience measures is still limited. Resilient solutions for transportation facilities vary greatly depending on the climate stressor, the specifics of a given site, and the availability of funding for implementation (see "Three Case Studies of Resilience Measures for Highway Facilities"). Building the business case for adaptation and aligning the required long-term investments with existing time frames for decision-making is difficult.[3,130,131] Uncertainties associated with projections of future climate hazards in specific geographic locations[130,132,133] and the lack of specific, detailed adaptation strategies[134] make assessment more complicated. However, in the wake of extreme events, some transportation agencies implemented resilience measures to withstand similar events in the future.

Future changes to and uncertainties about transportation technologies and transportation-related behaviors complicate agencies' ability to assess the adaptive capacity of transportation systems, their ability to withstand and recover from a disruption, and opportunities for cost-effective risk mitigation strategies (such as workplace telecommuting policies).

Case Study: Three Case Studies of Resilience Measures for Highway Facilities

In Florida, storm surges overwashing US 98 on Okaloosa Island undermined the highway foundation during Hurricane Ivan in 2004 and then again during other tropical storms in 2005. To prevent damage from overwash in the future, the Florida Department of Transportation installed buried erosion protection along the edge of the road. FHWA's analysis found that this proactive countermeasure was economically justified when it was done in 2006 and, further, that the benefit–cost ratio will quadruple over the next 50 years as sea levels continue to rise.[135]

Shore Road in Brookhaven, New York, is experiencing wave-induced bank erosion during storms. The road elevation is about 2 feet higher than the typical high tide today, and a recent study determined that constructing a coastal marsh can protect the roadway for decades at a low cost while enhancing ecosystems. At a later point, the town could increase the elevation of the road and install more expensive sheet pile walls or rock revetments if needed.[136]

In 2013 in Colorado, precipitation following wildfires caused massive debris flows that overwhelmed culverts and damaged US 24 (see Figure 12.4 for similar case). Recognizing the seriousness of this type of impact, engineering tools driven by future climate simulations were used to evaluate changing wildfire-induced debris flows and precipitation risks to culverts when rebuilding a similar highway (US 34). The best approach identified was to quickly adapt a culvert if and when a wildfire occurs in that watershed, with the goal of upsizing the structure before a rainfall event can cause it to fail. Adapting every culvert to account for wildfire risk would be prohibitively costly, especially given the high uncertainty and low probability that any particular culvert will be impacted by a wildfire over its service life.[72]

Flood Impacts on Colorado Highway

Figure 12.4: Flooding events can result in serious damage to road infrastructure. Here, debris flow covers US Highway 14 (Poudre Canyon) after the High Park Fire in 2012. Photo credit: Justin Pipe, Colorado Department of Transportation.

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Opening Image Credit

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Traceable Accounts

Process Description

We sought an author team that could bring diverse experiences and perspectives to the chapter, including some who have participated in prior national-level assessments within the sector. All are experts in the field of climate adaptation and transportation infrastructure. The team represents geographic expertise in the Northeast, Mid-Atlantic, South, Central, and Western regions, including urban and rural as well as coastal and inland perspectives. Team members come from the public (federal and city government and academia) and private sectors (consulting and engineering), with practitioner and research backgrounds.

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors at several workshops and teleconferences and via email exchanges. The authors considered inputs and comments submitted by the public, the National Academies of Sciences, Engineering, and Medicine, and federal agencies. For additional information on the overall report process, see Appendix 1: Process. The author team also engaged in targeted consultations with transportation experts during multiple listening sessions.

Because the impacts of climate change on transportation assets for the United States and globally have been widely examined elsewhere, including in the Third National Climate Assessment (NCA3),[137] this chapter addresses previously identified climate change impacts on transportation assets that persist nationally, with a focus on recent literature that describes newly identified impacts and advances in understanding. Asset vulnerability and impacts are of national importance because there are societal and economic consequences that transcend regional or subregional boundaries when a transportation network fails to perform as designed; a chapter focus is the emerging understanding of those impacts. Further, place-based, societally relevant understanding of transportation system resilience has been strongly informed by numerous recent local and state assessments that capture regionally relevant climate impacts on transportation and collectively inform national level risks and resilience. The chapter synthesizes the transportation communities' national awareness of and readiness for climate threats that are most relevant in the United States.

Key Message 1

Transportation at Risk

A reliable, safe, and efficient U.S. transportation system is at risk from increases in heavy precipitation, coastal flooding, heat, wildfires, and other extreme events, as well as changes to average temperature (*high confidence*). Throughout this century, climate change will continue to pose a risk to U.S. transportation infrastructure, with regional differences (*high confidence*).

Description of evidence base

Global mean sea level has risen since 1900 and is expected to continue to rise.[2] High tide flooding is increasing and is projected to continue increasing.[1] The peak storm surge levels are expected to rise more than the rise in sea level; models show that if the depth of storm flooding today is A and the rise in sea level between now and a future occurrence of an identical storm is B, then the

resulting future storm surge depths can be greater than A + B.[52] The U.S. roads and bridges in the coastal floodplain[49] are vulnerable today, as storms are repeatedly causing damage.[50,53,54,138] Sea level rise is also projected to impact ports,[57] airports,[58] and roads.[63,64,65] High tide flooding currently makes some roads impassable due to flooding[60,61] and is very likely to increase transportation disruptions in the future.[61]

In most parts of the United States, heavy precipitation is increasing in frequency and intensity, and more severe precipitation events are anticipated in the future.[25] Inland transportation infrastructure is highly vulnerable to intense rainfall and flooding.[3,25,66,67,69,139] In the western United States, large wildfires have increased and are likely to increase in the future,[70] escalating the vulnerability of transportation infrastructure to severe precipitation events.[71,72]

The frequency of summer heat waves has increased since the 1960s, and average annual temperatures have increased over the past three decades; these temperature changes are projected to continue to increase in the future.[41] Warming temperatures have increased costs[81] and reduced the performance of roads,[80] bridges,[4,5] railways,[4,5,6] and air transport.[3,74,86] Future temperature increases are projected to reduce infrastructure lifetime[78,79,122] and increase road costs.[12] Milder winters will likely lengthen the shipping season in northern inland ports,[87,88] benefit transportation safety,[42,43,44,66,82] and reduce winter maintenance.[4,12,45] In Alaska, however, permafrost thawing will damage roads[46] and increase the cost of roads (Ch. 26: Alaska).

Major uncertainties

Peer-reviewed literature on climate impacts to some assets is limited. Most literature addresses local- or regional-scale issues. Uncertainty in the ranges of climate change projection leads to challenges to quantifying impacts on transportation assets, which have long lifetimes.

Impacts to transportation infrastructure from climate change will depend on many factors, including population growth, economic demands, policy decisions, and technological changes. How these factors, with their potential compounding effects, as well as the impacts of disruptive or transformative technologies (such as automated vehicles or autonomous aerial vehicles), will contribute to transportation performance in the future is poorly understood.

The relationship among increases in large precipitation events and flood-induced infrastructure damage is uncertain because multiple factors (including land use, topography, and even flood control) impact flooding.[140,141,142,143] Hirsch and Ryberg (2012)[144] found limited evidence of increasing global mean carbon dioxide concentrations resulting in increasing flooding in any region of the United States. Archfield et al. (2016)[145] found that flood changes to date are fragmented and that a climate change signal on flood changes was not yet clear.

Description of confidence and likelihood

There is *very high confidence* that sea level rise and increases in flooding during coastal storms and astronomical high tides will lead to damage and service reductions with coastal bridges, roads, rails, and ports.

There is *high confidence* that heavy precipitation events have increased in intensity and frequency since 1901 (with the largest increase seen in the Northeast); this trend is projected to continue.[25] There is *medium confidence* that precipitation increases will lead to surface and rail transit delays

in urban areas. There is *medium confidence* that flood-induced damages to roads and bridges will increase.

Rising temperatures and extreme heat (*high confidence*) will damage pavement and increase railway and air transit delays. However, the actual magnitude of those impacts will depend on technological advancements and policy decisions about design and operations.

Key Message 2

Impacts to Urban and Rural Transportation

Extreme events that increasingly impact the transportation network are inducing societal and economic consequences, some of which disproportionately affect vulnerable populations (*high confidence*). In the absence of intervention, future changes in climate will lead to increasing transportation challenges, particularly because of system complexity, aging infrastructure, and dependency across sectors (*high confidence*).

Description of evidence base

The Key Message is largely supported by observation and empirical evidence that is well documented in the gray (non-peer-reviewed) literature and recent government reports. Because this is an important emerging area of research, the peer-reviewed scientific literature is sparse. Hence, much of the supporting materials for this Key Message are descriptions of impacts of recent events provided by news organizations and government summaries.

Many urban locations have experienced disruptive extreme events that have impacted the transportation network and led to societal and economic consequences. Louisiana experienced historic floods in 2016 that disrupted all modes of transportation and caused adverse impacts on major industries and businesses due to the halt of freight movement and employees' inability to get to work.[146] The 2016 floods that affected Texas from March to June resulted in major business disruption due to the loss of a major transportation corridor.[147] In 2017, Hurricane Harvey affected population and freight mobility in Houston, Texas, when 23 ports were closed and over 700 roads were deemed impassable.[148] Consequences of extreme events can be magnified when events are cumulative. The 2017 hurricanes impacting the southern Atlantic and Gulf Coasts and Puerto Rico created rising freight costs because freight carriers had to deal with poor traveling conditions, an unreliable fuel stock, and limited exports for the return trip.[149,150] Low-income populations have been linked to differences in perceived risks associated with an extreme event, in how they respond, and in their ability to evacuate or relocate.[151] Delays in evacuations can potentially lead to significant transportation delays, affecting the timeliness of first responders and evacuations. National- and local-level decision-makers are considering strategies during storm recovery and its aftermath to identify and support vulnerable populations to ensure transportation and access to schools, work, and community services (for example, the 2016 Baton Rouge flood event).

Similar to the urban and suburban scenarios, rural areas across the country have also experienced disruptions and impacts from climate events. Hurricane Irene resulted in the damage or destruction of roads throughout New England, resulting in small towns being isolated throughout the region.[152] Similarly, Hurricane Katrina devastated rural community infrastructure across the Gulf

Coast, which resulted in extended periods of isolation and population movement.[153] Lesser-known events are also causing regular impacts to rural communities, such as flood events in 2014 in Minnesota and in 2017 throughout the Midwest, which impacted towns for months due to damaged road infrastructure.[154,155]

Although flooding events and hurricanes receive significant attention, other weather-based events cause equal or greater impacts to rural areas. Landslide events have isolated rural communities by reducing them to single-road access.[156,157] Extreme heat events combined with drought have resulted in increases in wildfire activity that have impacted rural areas in several regions. The impacts of these wildfire events include damage to infrastructure both within rural communities and to access points to the communities.[158]

As documented, rural communities incur impacts from climate events that are similar to those experienced in urban and suburban communities. However, rural and isolated areas experience the additional concerns of recovering from extreme events with fewer resources and less capacity.[111] This difference often results in rural communities facing extended periods of time with limited access for commercial and residential traffic.

Major uncertainties

Realized societal and economic impacts from transportation disruptions vary by extreme event, depending on the intensity and duration of the storm; pre-storm conditions, including cumulative events; planning mechanisms (such as zoning practices); and so on. In addition, a combination of weather stressors, such as heavy precipitation with notable storm surge, can amplify effects on different assets, compounding the societal and economic consequences. These amplifications are poorly understood but directly affect transportation users. Interdependencies among transportation and other lifeline sectors can also have significant impacts on the degree of consequences experienced. These impacts are also poorly understood.

Description of confidence and likelihood

There is *medium to high confidence* that the urban setting can amplify heat.[159] There is also *medium to high confidence* that transportation networks are impacted by inland and coastal flooding.[70] There is *medium confidence* that socioeconomic conditions are strongly related to a population's resilience to extreme events.[151]

There is *high confidence* that impacts to the transportation network from extreme events are inducing societal and economic consequences, some of which disproportionately affect vulnerable populations (*medium confidence*). In the absence of intervention, projected changes in climate will likely lead to increasing transportation challenges as a result of system complexity, aging infrastructure with hundreds of billions of dollars in rehabilitation backlogs,[13] and dependency across sectors.

Key Message 3

Vulnerability Assessments

Engineers, planners, and researchers in the transportation field are showing increasing interest and sophistication in understanding the risks that climate hazards pose to transportation assets and services (*very high confidence*). Transportation practitioner efforts demonstrate the connection between advanced assessment and the implementation of adaptive measures, though many communities still face challenges and barriers to action (*high confidence*).

Description of evidence base

Chapter authors reviewed more than 60 recently published vulnerability assessments (details and links available through the online version of Figure 12.3) conducted by or for states and localities. The research approach involved internet searches, consultations with experts, and leveraging existing syntheses and compilations of transportation-related vulnerability assessments. The authors cast a broad net to ensure that as many assessments as possible were captured in the review. The studies were screened for a variety of metrics (for example, method of assessment, hazard type, asset category, vulnerability assessment type, economic analysis, and adaptation actions), and findings were used to inform the conclusions reached in this section.

Major uncertainties

Most of the literature and the practitioner studies cited for Key Message 3 were gray literature, which is not peer-reviewed but serves the purpose of documenting the state of the practice. This section was not an assessment of the science (that is, the validity of individual study results was not assessed) but surveyed how transportation practitioners are assessing and managing climate impacts. The conclusions are not predicated on selection of or relative benefits of specific modeling or technological advances.

Practitioners' motivations underlying changes in the state of the practice were derived from information in the studies and from cited literature. The authors of this section did not survey authors of individual vulnerability studies to determine their situation-specific motivations.

Description of confidence and likelihood

There is *high confidence* regarding the efforts of state and local transportation agencies to understand climate impacts through assessments like those referenced in Figure 12.3. There is *medium confidence* in the reasons for delay in implementing resilience measures and the motivations for vulnerability assessments. There is no consensus on how emerging transportation technologies will develop in the coming years and how this change will affect climate mitigation, adaptation, and resilience.

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13 Air Quality

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13 Air Quality

Carr Fire, Shasta County, California, August 2018

Key Message 1

Increasing Risks from Air Pollution

More than 100 million people in the United States live in communities where air pollution exceeds health-based air quality standards. Unless counteracting efforts to improve air quality are implemented, climate change will worsen existing air pollution levels. This worsened air pollution would increase the incidence of adverse respiratory and cardiovascular health effects, including premature death. Increased air pollution would also have other environmental consequences, including reduced visibility and damage to agricultural crops and forests.

Key Message 2

Increasing Impacts of Wildfires

Wildfire smoke degrades air quality, increasing the health risks to tens of millions of people in the United States. More frequent and severe wildfires due to climate change would further diminish air quality, increase incidences of respiratory illness from exposure to wildfire smoke, impair visibility, and disrupt outdoor recreational activities.

Key Message 3

Increases in Airborne Allergen Exposure

The frequency and severity of allergic illnesses, including asthma and hay fever, are likely to increase as a result of a changing climate. Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can increase exposure to airborne pollen allergens.

Key Message 4

Co-Benefits of Greenhouse Gas Mitigation

Many emission sources of greenhouse gases also emit air pollutants that harm human health. Controlling these common emission sources would both mitigate climate change and have immediate benefits for air quality and human health. Because methane is both a greenhouse gas and an ozone precursor, reductions of methane emissions have the potential to simultaneously mitigate climate change and improve air quality.

Executive Summary

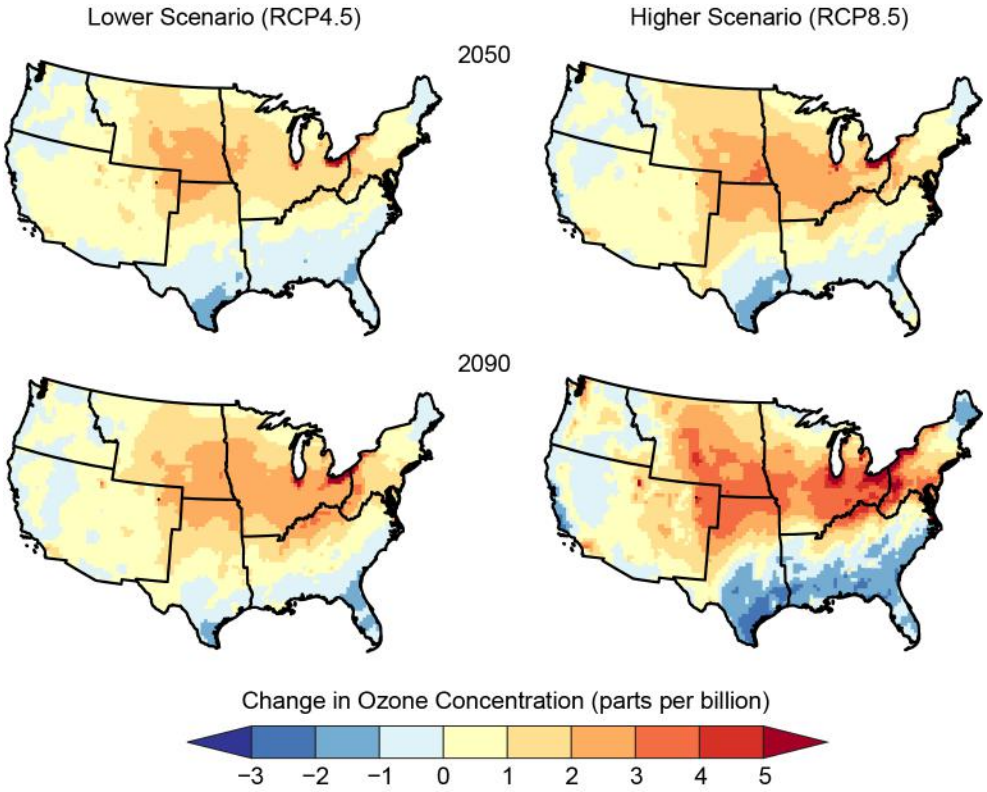
Unless offset by additional emissions reductions of ozone precursor emissions, there is high confidence that climate change will increase ozone levels over most of the United States, particularly over already polluted areas, thereby worsening the detrimental health and environmental effects due to ozone. The climate penalty results from changes in local weather conditions, including temperature and atmospheric circulation patterns, as well as changes in ozone precursor emissions that are influenced by meteorology. Climate change has already had an influence on ozone concentrations over the United States, offsetting some of the expected ozone benefit from reduced precursor emissions. The magnitude of the climate penalty over the United States could be reduced by mitigating climate change.

Climatic changes, including warmer springs, longer summer dry seasons, and drier soils and vegetation, have already lengthened the wildfire season and increased the frequency of large wildfires. Exposure to wildfire smoke increases the risk of respiratory disease, resulting in adverse impacts to human health. Longer fire seasons and increases in the number of large fires would impair both human health and visibility.

Climate change, specifically rising temperatures and increased carbon dioxide (CO_2) concentrations, can influence plant-based allergens, hay fever, and asthma in three ways: by increasing the duration of the pollen season, by increasing the amount of pollen produced by plants, and by altering the degree of allergic reactions to the pollen.

The energy sector, which includes energy production, conversion, and use, accounts for 84% of greenhouse gas (GHG) emissions in the United States as well as 80% of emissions of nitrogen oxides (NO_x) and 96% of sulfur dioxide, the major precursor of sulfate aerosol. In addition to reducing future warming, reductions in GHG emissions often result in co-benefits (other positive effects, such as improved air quality) and possibly some negative effects (disbenefits) (Ch. 29: Mitigation). Specifically, mitigating GHG emissions can lower emissions of particulate matter (PM), ozone and PM precursors, and other hazardous pollutants, reducing the risks to human health from air pollution.

Projected Changes in Summer Season Ozone



The maps show projected changes in summer averages of the maximum daily 8-hour ozone concentration (as compared to the 1995–2005 average). Summertime ozone is projected to change non-uniformly across the United States based on multiyear simulations from the Community Multiscale Air Quality (CMAQ) modeling system. Those changes are amplified under the higher scenario (RCP8.5) compared with the lower scenario (RCP4.5), as well as at 2090 compared with 2050. Data are not available for Alaska, Hawai'i, U.S.-Affiliated Pacific Islands, and the U.S. Caribbean. *From Figure 13.2 (Source: adapted from EPA 2017[1]).*

State of the Sector

Air quality is important for human health, vegetation, and crops as well as aesthetic considerations (such as visibility) that affect appreciation of the natural beauty of national parks and other outdoor spaces. Many of the processes that determine air quality are affected by weather (Figure 13.1). For example, hot, sunny days can increase ozone levels, while stagnant weather conditions can produce high concentrations of both ozone and particulate matter (PM). Ozone and PM are air pollutants that adversely affect human health and are monitored and regulated with national standards. Temperature, wind patterns, cloud cover, and precipitation, as well as the amounts and types of pollutants emitted into the air from human activities and natural sources, all affect air quality (Figure 13.1). Thus, climate-driven changes in weather, human activity, and natural emissions are all expected to impact future air quality across the United States.

These climate effects on air quality are not expected to occur uniformly at all locations. For example, as discussed in Chapter 2: Climate, precipitation is projected to increase in some regions of the country and decrease in other regions. Regions that experience excessive periods of drought and higher temperatures will have increased frequency of wildfires and more windblown dust from soils. At the same time, changes to temperatures and rainfall affect the types of crops that can be grown (Ch. 10: Ag & Rural) and the length of the growing season, the application of fertilizers and pesticides to crops, and ensuing transport and fate of those chemicals into the air, water, and soil. In the future, climate change is expected to alter the demand for heating and cooling of indoor spaces due to changes in temperatures. The resulting shift in fuel types and amounts used will modify the amount and composition of air pollutants emitted. Climate change can also increase the duration of the pollen season and the amount of pollen at some locations, as well as worsen respiratory health impacts due to pollen exposure. Despite the potential variability in regional impacts of climate change, there is evidence that climate change will increase the risk of unhealthy air quality in the future across the Nation in the absence of further air pollution control efforts (for other impacts of climate change on health, see Ch. 14: Human Health).

Since people spend most of their time inside buildings, indoor air quality is important for human health. Indoor air pollutants may come from interior sources or may be transported into buildings with outdoor air. If there are changes in airborne pollutants of outdoor origin, such as ozone, pollen, mold, and $PM_{2.5}$ (particulate matter less than 2.5 micrometers in diameter), there will be changes in indoor exposures to these contaminants.[2,3]

There is robust evidence from models and observations that climate change is worsening ozone pollution. The net effect of climate change on PM pollution is less certain than for ozone, but increases in smoke from wildfires and windblown dust from regions affected by drought are expected. The complex interactions of natural variability with changes in climate and emissions pose a significant challenge for air quality management. Some approaches to mitigating climate change could result in large near-term co-benefits for air quality.

Pathways by Which Climate Change Will Influence Air Pollution

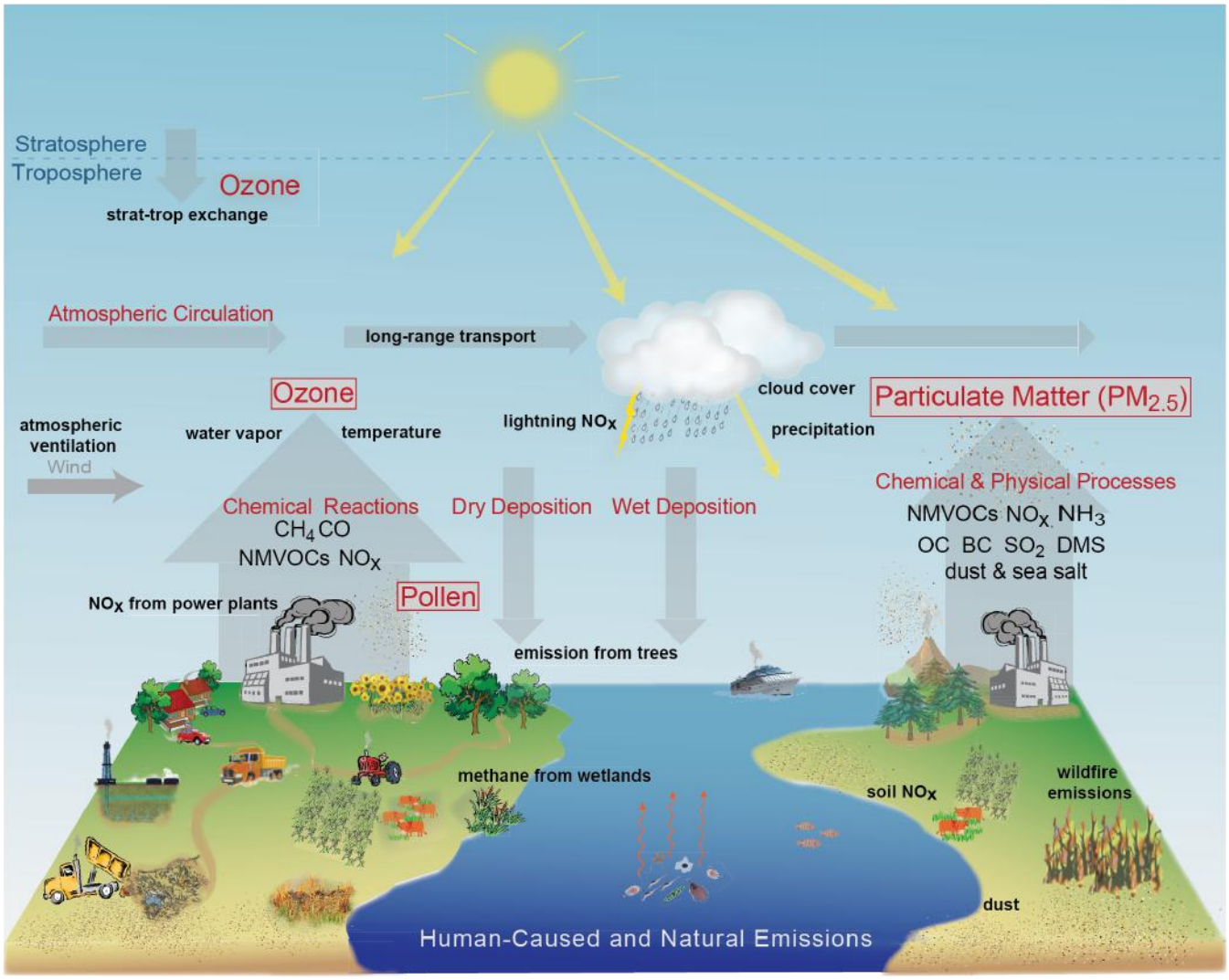


Figure 13.1: Climate change will alter (black bold text) chemical and physical interactions that create, remove, and transport air pollution (red text and gray arrows). Human activities and natural processes release precursors for ground-level ozone (O_3) and particulate matter with a diameter less than 2.5 micrometers ($PM_{2.5}$), including methane (CH_4), carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), sulfur dioxide (SO_2), ammonia (NH_3), organic carbon (OC), black carbon (BC), and dimethyl sulfide (DMS); and direct atmospheric pollutants, including mineral dust, sea salt, pollen, spores, and food particles. Source: adapted from Fiore et al. 2015.[4] Reprinted by permission of the publisher (Taylor & Francis Ltd., http://www.tandfonline.com).

Air Pollution Health Effects

Ground-level ozone and particulate matter are common air pollutants that pose a serious risk to human health and the environment.[5,6] Short- and long-term exposure to these pollutants results in adverse respiratory and cardiovascular effects,[7] including premature deaths,[8] hospital and emergency room visits, aggravated asthma,[3,9] and shortness of breath.[10] Certain population groups, such as the elderly, children, and those with chronic illnesses, are especially susceptible to ozone and PM-related effects.[11,12,13]

A growing body of evidence indicates the harmful effects of short-term (i.e., daily) exposures to ground-level ozone vary with climate conditions, specifically temperature.[14,15,16,17,18] For a given level of ozone, higher temperatures increase the risk of ozone-related premature death.[14,19,20,21] However, the risk of premature death is likely to decrease

as the prevalence of air conditioning increases, as is expected to occur with rising temperatures.[22] The extent to which the growing use of air conditioning will offset climate-induced increases in ozone-related premature death is unknown.

Ozone Air Quality

Ozone is not directly emitted but is formed in the atmosphere by reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Ozone concentrations depend on emissions of these two precursors as well as weather conditions such as temperature, humidity, cloud cover, and winds.[3] These emissions come from a variety of human sources, such as power plants and motor vehicles, and from natural sources, such as forests and wildfires (Figure 13.1). Additionally, ozone concentrations in one region may be influenced by the transport of either precursors or ozone itself from another region.[23,24]

Ozone levels in the United States are often highest in Southern California and the Northeast Corridor as well as around other large cities like Dallas, Houston, Denver, Phoenix, and Chicago,[25] and during extended episodes of extreme heat and sunshine.[26] Ozone air quality in the United States has improved dramatically over the past few decades due to NO_x and VOC emissions control efforts, despite population and economic growth.[27,28,29] Nationally, ozone concentrations have been reduced by 22% over the 1990 to 2016 period.[29] Nonetheless, in 2015 nearly 1 in 3 Americans were exposed to ozone values that exceeded the national standard determined by the U.S. Environmental Protection Agency (EPA) to be protective of human health.[29] Adverse human health impacts associated with exposure to ground-level ozone include premature death, respiratory hospital admissions, cases of aggravated asthma, lost days of school, and reduced productivity among outdoor workers.[30,31,32] Ozone pollution can also damage crops and plant communities, including forests, by reducing photosynthesis.[33]

Due in part to air pollutant regulations driven by the Clean Air Act, NO_x and VOC emissions from human sources should continue to decline over the next few decades.[34] These emissions reductions are designed to reduce ozone concentrations so that polluted areas of the country meet air quality standards. However, climate change will also influence future levels of ozone in the United States by altering weather conditions and impacting emissions from human and natural sources. The prevailing evidence strongly suggests that climate change alone introduces a climate penalty (an increase in air pollution resulting from climate change[35,36]) for ozone over most of the United States from warmer temperatures and increases in natural emissions.[3,4,37,38] This climate penalty will partially counteract the continued reductions in emissions of ozone precursors from human activities.

Particulate Matter

Tiny liquid or solid particles suspended in the atmosphere are known as aerosols or particulate matter (PM). PM includes many different chemical components, such as sulfate, nitrate, organic and black carbon, mineral dust, and sea spray. Unlike ozone, PM can be either directly emitted or formed in the atmosphere. $PM_{2.5}$ refers to atmospheric PM with a diameter less than 2.5 micrometers. These particles are small enough to be inhaled deeply, and exposure to high concentrations can result in serious health impacts, including premature death, nonfatal heart attacks, and adverse birth outcomes.[5,39,40,41] $PM_{2.5}$ concentrations vary greatly with daily weather conditions,[42,43] depending particularly on wind speed (which affects the mixing of pollutants) and precipitation (which removes particles from the air).[4] Concentrations of $PM_{2.5}$ build up during long periods of

low wind speeds, and they are reduced when weather fronts move air through a region.[4]

Wildfires not only emit gases that contribute to ozone formation[44,45,46,47,48] but they also are a major source of PM, especially in the western United States during the summer[49,50,51,52,53,54,55] and in the Southeast[48,56] (Ch. 6: Forests; Ch. 19: Southeast, Case Study "Prescribed Fire"; Ch. 24: Northwest; Ch. 25: Southwest). Wildfire smoke can worsen air quality locally,[57] with substantial public health impacts in regions with large populations near heavily forested areas.[56,58,59,60,61] Exposure to wildfire smoke increases the incidence of respiratory illnesses, including asthma, chronic obstructive pulmonary disease, bronchitis, and pneumonia.[62] Smoke can decrease visibility[63] and can be transported hundreds of miles downwind, often crossing national boundaries.[54,64,65,66,67,68,69]

Climate change is expected to impact atmospheric PM concentrations in numerous ways.[38,70] Changing weather patterns, including increased stagnation,[71,72] altered frequency of weather fronts,[73,74] more frequent heavy rain events,[43] changing emissions from vegetation[75,76] and human sources,[77] and increased evaporation of some aerosol components[78] will all affect PM concentrations. In addition, more frequent and longer droughts would lengthen the wildfire season[79,80,81] and result in larger wildfires[82,83] and increased dust emissions in some areas.[84] Projections of regional precipitation changes show considerable variation across models and thus remain highly uncertain.[85] Accurately assessing how $PM_{2.5}$ concentrations will respond to the changing climate is difficult due to these complex and highly spatially variable interactions.

Key Message 1

Increasing Risks from Air Pollution

More than 100 million people in the United States live in communities where air pollution exceeds health-based air quality standards. Unless counteracting efforts to improve air quality are implemented, climate change will worsen existing air pollution levels. This worsened air pollution would increase the incidence of adverse respiratory and cardiovascular health effects, including premature death. Increased air pollution would also have other environmental consequences, including reduced visibility and damage to agricultural crops and forests.

Unless offset by additional reductions of ozone precursor emissions, there is high confidence that climate change will increase ozone levels over most of the United States, particularly over already polluted areas,[3,86] thereby worsening the detrimental health and environmental effects due to ozone. Although competing meteorological effects determine local ozone levels, temperature is often the largest single driver.[87] The climate penalty[35,36] results from changes in local weather conditions, including temperature and atmospheric circulation patterns,[4,88] as well as changes in ozone precursor emissions that are influenced by meteorology.[75,76,77] Climate change has already had an influence on ozone concentrations over the United States, offsetting some of the expected ozone benefit from reduced precursor emissions.[89,90] Assessments of climate change impacts on ozone trends are complicated by year-to-year changes in weather conditions[91] and require multiple years of model information to estimate the potential range of effects.[92] Besides being affected by climate change, future ozone levels in the United States will also be affected greatly by

domestic emissions of ozone precursors as well as by international emissions of ozone precursors and global methane levels. Studies suggest that climate change will decrease the sensitivity of regional ozone air quality to intercontinental sources.[93]

$PM_{2.5}$ accounts for most of the health impacts due to air pollution in the United States,[94] and small changes in average concentrations have large implications for public health. Without consideration of climate effects, concentrations of $PM_{2.5}$ in the United States are projected to decline through 2040 due to ongoing emissions control efforts.[34] $PM_{2.5}$ is highly sensitive to weather conditions, including temperature, humidity, wind speed, and rainfall. The effects of climate change on the timing, intensity, duration, and frequency of rainfall are highly uncertain, influencing both the removal of $PM_{2.5}$ from air and the incidence of wildfires and their associated emissions. Accordingly, the net impact of climate-driven weather changes on $PM_{2.5}$ concentrations is less certain than for ozone.[3,4,43,70] However, some studies have indicated that even without considering increased wildfire frequency, climate change will cause a small but important increase in $PM_{2.5}$ over North America.[95,96] The impact of climate change on the $PM_{2.5}$ contribution from intercontinental sources, which depends strongly on projected changes in precipitation, remains highly uncertain.[24]

The health impacts of climate-induced changes in air quality may be reduced by various adaptation measures. For example, as local authorities issue air quality alerts, people may reduce their exposure to air pollution by postponing outdoor activities and staying indoors (for further information on the role of adaptation in reducing climate-related health risks, see Ch. 14: Human Health, KM 3).

The magnitude of the climate penalty over the United States could be reduced by mitigating climate change.[1,90,97] For example, Figure 13.2 shows results from one study[1] projecting the change in summertime ozone resulting from two different future scenarios (RCP8.5 and RCP4.5) (see the Scenario Products section of App. 3 for additional information about these scenarios) at 2050 and 2090, with human emissions of ozone precursors held constant. Due to climate change, ozone is projected to increase over a broad portion of the United States. Mitigating climate change globally (for instance, following RCP4.5 rather than RCP8.5) would reduce the impact on ozone, resulting in fewer adverse health effects, including 500 fewer premature deaths per year due to ozone in 2090.[1]

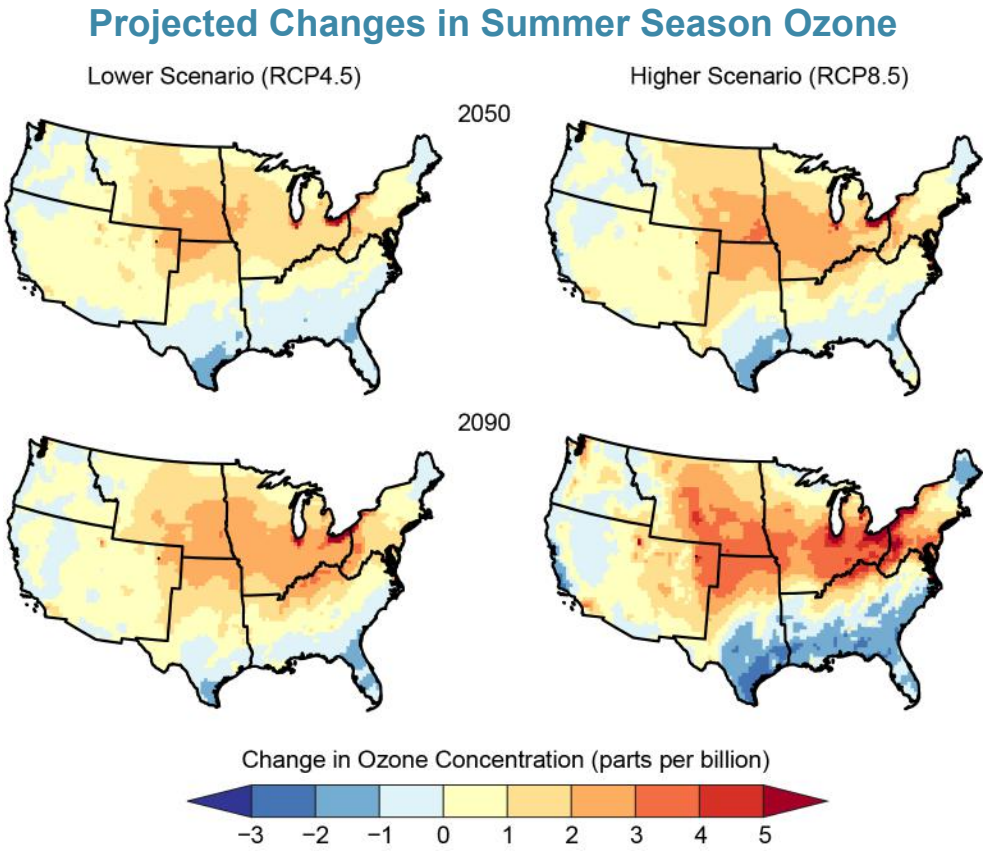


Figure 13.2: The maps show projected changes in summer averages of the maximum daily 8-hour ozone concentration (as compared to the 1995–2005 average). Summertime ozone is projected to change non-uniformly across the United States based on multiyear simulations from the Community Multiscale Air Quality (CMAQ) modeling system. Those changes are amplified under the higher scenario (RCP8.5) compared with the lower scenario (RCP4.5), as well as at 2090 compared with 2050. Data are not available for Alaska, Hawai'i, U.S.-Affiliated Pacific Islands, and the U.S. Caribbean. Source: adapted from EPA 2017.[1]

Key Message 2

Increasing Impacts of Wildfires

Wildfire smoke degrades air quality, increasing the health risks to tens of millions of people in the United States. More frequent and severe wildfires due to climate change would further diminish air quality, increase incidences of respiratory illness from exposure to wildfire smoke, impair visibility, and disrupt outdoor recreational activities.

Climatic changes, including warmer springs, longer summer dry seasons, and drier soils and vegetation, have already lengthened the wildfire season[79,80,81,98] (Ch. 6: Forests) and increased the frequency of large wildfires.[82,83] Human-caused climate change is estimated to have doubled the area of forest burned in the western United States from 1984 to 2015.[99] Projections indicate that the wildfire frequency and burned area in North America will continue to increase over the 21st century due to climate change.[100,101,102,103,104,105,106]

Wildfires and prescribed fires contribute to ozone formation[44,107] and are major sources of PM, together comprising about 40% of directly emitted $PM_{2.5}$ in the United States in 2011.[34] Exposure to wildfire smoke increases the risk of respiratory disease and mortality.[56,60,62] Longer fire seasons and increases in the number of large fires would impair both human health[108] and visibility.[54,63] Wildfires are projected to become the principal driver of summertime

$PM_{2.5}$ concentrations, offsetting even large reductions in emissions of $PM_{2.5}$ precursors.[54,109]

Opportunities for outdoor recreational activities are also vulnerable to changes in the frequency and intensity of wildfires due to climate change. Climate change-induced increases in wildfire smoke events are likely to reduce the amount and quality of time spent in outdoor activities (Ch. 22: N. Great Plains, KM 3; Ch. 24: Northwest, KM 4). More accurate forecasting of smoke events may mitigate some of the negative effects through changes in timing of outdoor activities.

Forests are actively managed, and the frequency and severity of wildfire occurrence in the future will not be determined solely by climate factors. Humans affect fire activity in many ways, including increasing ignitions and conducting controlled burns and fire suppression.[110,111] Forest management decisions may outweigh the impacts of climate change on both forest ecosystems and air quality.[112]

Key Message 3

Increases in Airborne Allergen Exposure

The frequency and severity of allergic illnesses, including asthma and hay fever, are likely to increase as a result of a changing climate. Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can increase exposure to airborne pollen allergens.

Climate change, specifically rising temperatures and increased CO_2 concentrations, can influence plant-based allergens, hay fever, and asthma in three ways: by increasing the duration of the pollen season, by increasing the amount of pollen produced by plants, and by altering the degree of allergic reactions to pollen.

Seasonally, airborne allergen (aeroallergen) exposure in the United States begins with the release of tree pollen in the spring. Between the 1950s and the early 2000s, warming winters and earlier arrival of springs have resulted in earlier flowering of oak trees.[113] Projected increases in CO_2 induce earlier and greater seasonal pollen production in pine trees[114] and oak trees.[115] For summer pollen producers, such as weeds and grasses, the effect of warming temperatures on earlier flowering is less evident. However, the allergen content of timothy grass pollen increases with concurrent increases in ozone and CO_2.[116] For common ragweed, the primary fall aeroallergen, greenhouse studies simulating increased temperature and CO_2 concentrations resulted in earlier flowering, greater floral numbers, increased pollen production, and enhanced allergen content of the pollen.[117,118,119,120] Regional and continental studies indicate that ragweed growth and pollen production increase with urban-induced increases in temperature and CO_2. Ragweed pollen season exposure varies as a function of latitude and delayed autumnal frosts in North America.[119,121] In addition to pollen, aeroallergens are also generated by molds. Plants are often affected, since they can serve as hosts for fungi. For example, projected end-of-century CO_2 concentrations would substantially increase the number of allergenic spores produced from timothy grass.[122]

Although warming temperatures and rising CO_2 levels clearly increase aeroallergen prevalence, the link between exposure and health impacts is less well established. However, hay fever prevalence has been associated with exposure to annual and seasonal extreme heat events.[123] Furthermore, climate-induced changes in oak pollen are projected to increase the number of

asthma-related emergency department visits in the Northeast, Southwest, and Midwest.[115]

Key Message 4

Co-Benefits of Greenhouse Gas Mitigation

Many emission sources of greenhouse gases also emit air pollutants that harm human health. Controlling these common emission sources would both mitigate climate change and have immediate benefits for air quality and human health. Because methane is both a greenhouse gas and an ozone precursor, reductions of methane emissions have the potential to simultaneously mitigate climate change and improve air quality.

The energy sector, which includes energy production, conversion, and use, accounts for 84% of greenhouse gas (GHG) emissions[124] as well as 80% of emissions of NO_x and 96% of sulfur dioxide, the major precursor of sulfate aerosol.[125] In addition to reducing future warming, reductions in GHG emissions often result in co-benefits (other positive effects, such as improved air quality) and possibly some negative effects (disbenefits) (Ch. 29: Mitigation). Specifically, mitigating GHGs can lower emissions of PM, ozone and PM precursors, and other hazardous pollutants, reducing the risks to human health from air pollution.[97,126,127,128,129,130] However, the magnitude of air quality co-benefits depends on a number of factors. Areas with higher levels of air pollution have more potential for air quality co-benefits compared to areas where emission controls have been enacted and air pollution levels have been reduced.[131] Different approaches to GHG mitigation yield different reductions, or in some cases, increases in ozone and PM precursors.[132] For example, diesel vehicles emit less GHGs than gasoline-powered vehicles, but without correctly operating pollution-control devices, diesel vehicles emit more particles and ozone precursors and thus contribute more to air quality human health risks.[133]

In addition to co-benefits from sources that emit multiple pollutants, mitigating individual GHGs could yield co-benefits. For example, methane is both a GHG and a slowly reactive ozone precursor that contributes to global background surface ozone concentrations. Some monitoring stations in remote parts of the western United States have recorded rising ozone concentrations, resulting in part from increased global methane levels.[90] The magnitude of the human health benefit of lowering ozone levels via methane mitigation is substantial and is similar in value to the climate change benefits.[134,135] Additionally, PM influences climate on local to global scales by affecting the radiation balance of the Earth,[23,136] so controlling emissions of PM and its precursors would not only yield direct human health benefits via reduced exposure but also avoid or minimize local meteorological conditions that lead to a buildup of pollutants.[137]

Acknowledgments

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Traceable Accounts

Process Description

Due to limited resources and requirements imposed by the Federal Advisory Committee Act, the decision was made that this chapter would be developed using an all-federal author team. The author team was selected based on expertise in climate change impacts on air quality; several of the chapter authors were authors of the "Air Quality Impacts" chapter of the U.S. Global Change Research Program's (USGCRP) Climate and Health Assessment.[3] This chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors via weekly teleconferences and email exchanges. The authors considered inputs and comments submitted by the public; the National Academies of Sciences, Engineering, and Medicine; and federal agencies.

Key Message 1

Increasing Risks from Air Pollution

More than 100 million people in the United States live in communities where air pollution exceeds health-based air quality standards. Unless counteracting efforts to improve air quality are implemented, climate change will worsen existing air pollution levels (*likely, high confidence*). This worsened air pollution would increase the incidence of adverse respiratory and cardiovascular health effects, including premature death (*high confidence*). Increased air pollution would also have other environmental consequences, including reduced visibility and damage to agricultural crops and forests (*likely, very high confidence*).

Description of evidence base

It is well established that air pollutants pose a serious risk to human health and the environment.[5,6] Short- and long-term exposure to pollutants such as ozone or $PM_{2.5}$ results in premature deaths,[8] hospital and emergency room visits, aggravated asthma,[3,9] and shortness of breath.[10] Numerous air quality modeling studies have assessed the potential impacts of a changing climate on future ozone and particulate matter levels in the United States.[4,37,38,70,86] These studies examine simulations conducted with a broad ensemble of global and regional climate models under various potential climate scenarios. For ozone, these model assessments consistently project higher future levels commensurate with warmer climates, independent of varying individual model assumptions. This model consensus strengthens confidence in the projected signal. Additionally, well-established data analyses have shown a strong positive correlation between temperature and ozone at many locations in the United States.[87,89] Although competing meteorological effects determine local ozone levels, temperature is often the single largest meteorological driver. This present-day signal also bolsters confidence in the conclusion that warmer climates will be associated with higher ozone. There are also modeling and observational studies that demonstrate that ozone precursor emissions from natural[75] and human sources[77] increase with temperature. In aggregate, the consistency in the ozone response to past and projected future climate across a large volume of analyses provides high confidence that ozone air pollution will likely be worsened in a warmer climate. For particulate matter, the model assessments exhibit greater variability in terms of future concentration differences projected to result from meteorological changes in a warmer

climate.[3,4,43,70] The reduced certainty in the response of $PM_{2.5}$ concentrations (particulate matter, or PM, less than 2.5 micrometers in diameter) to changing meteorological drivers is the result of the multiple pathways toward $PM_{2.5}$ formation and the variable influence of meteorological factors on each of those different pathways.[5] Most of these model assessments have not considered the impact of changes in PM from changes in wildfires or windblown dust because they are difficult to quantify. Studies that have included projections of future wildfire incidences have concluded that climate-driven increases in wildfire activity are *likely*, with wildfires becoming an increasingly important source of $PM_{2.5}$[63,108,109] and degrading visibility.[54] Finally, there is ample observational evidence that decreasing ozone and particulate precursor emissions would reduce pollutant levels.[28,29]

Major uncertainties

Model simulations of future air quality indicate that climate warming generally increases ground-level ozone across the United States (see Figure 13.2), but results differ spatially and in the magnitude of the projected signal.[90,138,139,140,141] Because meteorological influences on ozone formation can vary to some degree by location (for example, wind direction may be paramount in locations affected primarily by ozone transport), a few areas may experience lower ozone levels.[4] Future ozone levels over the United States will depend not only on the severity of the climate change impacts on meteorology favorable for ozone accumulation but also on any measures to reduce ozone precursor emissions, introducing further uncertainty. Even larger uncertainties exist with respect to the climate impacts on $PM_{2.5}$, where the future concentrations will depend on changes in a suite of meteorological factors, which in some cases (for example, precipitation) are more difficult to quantify.

Description of confidence and likelihood

There is *high confidence* that rising temperatures will *likely* increase future ozone levels in many parts of the United States in response to climate change. There is greater uncertainty that a warmer climate will increase future $PM_{2.5}$ levels over the United States. Ultimately, the actual ozone and $PM_{2.5}$ changes between the present and the future at any given location will depend on the local climate impacts on meteorology and pollutant emission controls in that region. There is *very high confidence* that reducing ozone precursor emissions and $PM_{2.5}$ precursors and/or direct emissions will *likely* lead to improved air quality in the future, thus mitigating adverse climate effects.

Key Message 2

Increasing Impacts of Wildfires

Wildfire smoke degrades air quality, increasing the health risks to tens of millions of people in the United States. More frequent and severe wildfires due to climate change would further diminish air quality, increase incidences of respiratory illness from exposure to wildfire smoke, impair visibility, and disrupt outdoor recreational activities (*very likely, high confidence*).

Description of evidence base

Wildfire smoke worsens air quality through its direct emissions to the atmosphere as well as through chemical reactions of those pollutants with sunlight and other pollutants. Exposure to wildfire smoke increases the risk of exacerbating respiratory illnesses in tens of millions of people in vulnerable population groups across the United States.[62] Several studies have indicated that climate change has already led to longer wildfire seasons,[79] increased frequency of large wildfires,[82,83] and increased area of forest burned.[99] Additional studies project that climate change will cause wildfire frequency and burned area in North America to increase over the 21st century.[81,100,101,102,103,104,105,106] Increased emissions from wildfires may offset the benefits of large reductions in emissions of $PM_{2.5}$ precursors.[54,109] There is a broad and consistent evidence base leading to a high confidence conclusion that the increasing impacts of wildfire are very likely. Increases in wildfire smoke events due to climate change would reduce opportunities for outdoor recreational activities (Ch. 22: N. Great Plains, KM 3; Ch. 24: Northwest, KM 4).

Major uncertainties

Humans affect fire activity in many ways, including increasing ignitions as well as conducting controlled burns and fire suppression activities.[110,111] The frequency and severity of wildfire occurrence in the future will be largely determined by forest management practices and climate adaptation measures, which are very uncertain. Housing development practices and changes in the urban–forest interface are also important factors for future wildfire occurrence and for the extent to which associated smoke emissions impair air quality and result in adverse health effects. The composition of the pollutants contained in wildfire smoke and their chemical reactions are highly dependent on a variety of environmental factors, so projecting and quantifying the effects of wildfire smoke on specific pollutants can be particularly challenging. Exposure to wildfire smoke may also increase the risk of cardiovascular illness, but additional data are required to quantify this risk.[62] More accurate forecasting of wildfire smoke events may mitigate health impacts and reduced opportunities for outdoor recreational activities through changes in timing of those activities.

Description of confidence and likelihood

There is *high confidence* that rising temperatures and earlier spring snowmelt will *very likely* result in lengthening the wildfire season in portions of the United States, leading to an increased frequency of wildfires and associated smoke. There is *very high confidence* that increasing exposure to wildfire smoke, which contains particulate matter, will increase adverse health impacts. It is *likely* that smoke from wildfires will reduce visibility and disrupt outdoor recreational activities.

Key Message 3

Increases in Airborne Allergen Exposure

The frequency and severity of allergic illnesses, including asthma and hay fever, are likely to increase as a result of a changing climate. Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can increase exposure to airborne pollen allergens. (*Likely, High Confidence*)

Description of evidence base

Considerable evidence supports the conclusion that climate change and rising levels of CO_2 affect key aspects of aeroallergen biology, including the production, temporal distribution, and potential allergenicity of aeroallergens.[142,143,144,145,146] This evidence includes historical trends indicating that climate change has altered seasonal exposure times for allergenic pollen.[113] These changes in exposure times are associated with rising CO_2 levels, higher temperatures, changes in precipitation (which can extend the start or duration of pollen release times), and the amount of pollen released, the allergenicity of the pollen, and the spatial distribution of that pollen.[117,118,119,147]

Specific changes in weather patterns or extremes are also likely to contribute to the exacerbation of allergy symptoms. For example, thunderstorms can induce spikes in aeroallergen concentrations and increase the incidence and severity of asthma and other allergic disease.[148,149] However, the specific mechanism for intensification of weather and allergic disease is not entirely understood.

Overall, climate change and rising CO_2 levels are likely to increase exposure to aeroallergens and contribute to the severity and prevalence of allergic disease, including asthma.[115] There is consistent and compelling evidence that exposure to aeroallergens poses a significant health risk in regard to the occurrence of asthma, hay fever, sinusitis, conjunctivitis, hives, and anaphylaxis.[150,151,152,153] Finally, there is evidence that synergies between aeroallergens and air pollution, especially particulate matter, may increase health risks for individuals who are simultaneously exposed.[154,155,156]

Major uncertainties

While specific climate- and/or CO_2-induced links to aeroallergen biology are evident, allergic diseases develop in response to complex and multiple interactions, including genetic and non-genetic factors, a developing immune system, environmental exposures (such as ambient air pollution or weather conditions), and socioeconomic and demographic factors. Overall, the role of these factors in eliciting a health response has not been entirely elucidated. However, recent evidence suggests that climate change and aeroallergens are having a discernible impact on public health.[123,157]

There are a number of areas where additional information is needed, including regional variation in climate and aeroallergen production; specific links between aeroallergens and related diseases, particularly asthma; the need for standardized approaches to determine exposure times and pollen concentration; and uncertainty regarding the role of CO_2 on allergenicity.

Description of confidence and likelihood

The scientific literature shows that there is *high confidence* that changes in climate, including rising temperatures and altered precipitation patterns as well as rising levels of atmospheric CO_2, will increase the concentration, allergenicity, season length, and spatial distribution of a number of aeroallergens. These changes in aeroallergen exposure are, in turn, *likely* to impact allergic disease.

Key Message 4

Co-Benefits of Greenhouse Gas Mitigation

Many emission sources of greenhouse gases also emit air pollutants that harm human health. Controlling these common emission sources would both mitigate climate change and have immediate benefits for air quality and human health. Because methane is both a greenhouse gas and an ozone precursor, reductions of methane emissions have the potential to simultaneously mitigate climate change and improve air quality. (*Very Likely, Very High Confidence*)

Description of evidence base

Decades of experience in air quality management have resulted in a detailed accounting of the largest emission sources of greenhouse gases (GHGs) and precursors of ozone and PM. The cost and effectiveness of emission control technologies for the largest emissions sources are well understood. By combining these emission and control technology data with energy system modeling tools, the potential to achieve benefits to air quality while mitigating GHG emissions under a range of scenarios has been quantified in numerous studies.

Major uncertainties

A wide range of values have been reported for the magnitude of air quality co-benefits. Much of this variability can be attributed to differences in the mix of co-benefits included in the analysis and the time period under consideration. The largest sources of uncertainty are the cost paths of different energy technologies over time and the extent to which policy choices impact the evolution of these costs and the availability of different energy technologies.

Description of confidence and likelihood

There is *very high confidence* that emissions of ozone and PM precursors could be reduced by reducing combustion sources of CO_2. Reducing emissions of ozone and PM precursors would be *very likely* to reduce ozone and PM pollution, which would *very likely* result in fewer adverse health effects from air pollution. There is *very high confidence* that controlling methane emissions would also reduce ozone formation rates, which would also *very likely* lead to lower ozone levels.

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On the Web: https://nca2018.globalchange.gov/chapter/health

14 Human Health

Algal bloom in Lake Erie in the summer of 2015

Key Message 1

Climate Change Affects the Health of All Americans

The health and well-being of Americans are already affected by climate change, with the adverse health consequences projected to worsen with additional climate change. Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.

Key Message 2

Exposure and Resilience Vary Across Populations and Communities

People and communities are differentially exposed to hazards and disproportionately affected by climate-related health risks. Populations experiencing greater health risks include children, older adults, low-income communities, and some communities of color.

Key Message 3

Adaptation Reduces Risks and Improves Health

Proactive adaptation policies and programs reduce the risks and impacts from climate-sensitive health outcomes and from disruptions in healthcare services. Additional benefits to health arise from explicitly accounting for climate change risks in infrastructure planning and urban design.

Key Message 4

Reducing Greenhouse Gas Emissions Results in Health and Economic Benefits

Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term. By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions.

Executive Summary

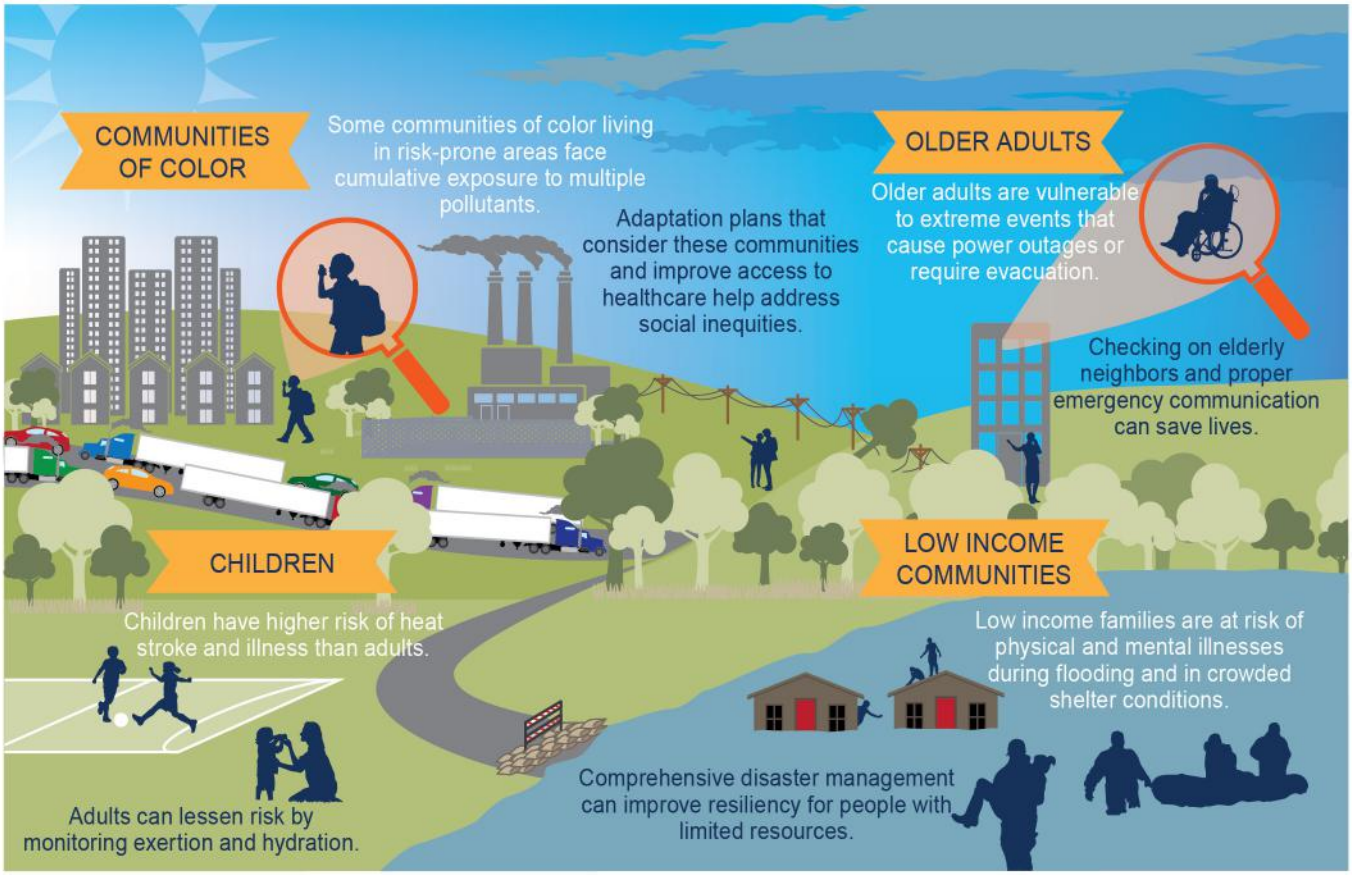
Climate-related changes in weather patterns and associated changes in air, water, food, and the environment are affecting the health and well-being of the American people, causing injuries, illnesses, and death. Increasing temperatures, increases in the frequency and intensity of heat waves (since the 1960s), changes in precipitation patterns (especially increases in heavy precipitation), and sea level rise can affect our health through multiple pathways. Changes in weather and climate can degrade air and water quality; affect the geographic range, seasonality, and intensity of transmission of infectious diseases through food, water, and disease-carrying vectors (such as mosquitoes and ticks); and increase stresses that affect mental health and well-being.

Changing weather patterns also interact with demographic and socioeconomic factors, as well as underlying health trends, to influence the extent of the consequences of climate change for individuals and communities. While all Americans are at risk of experiencing adverse climate-related health outcomes, some populations are disproportionately vulnerable.

The risks of climate change for human health are expected to increase in the future, with the extent of the resulting impacts dependent on the effectiveness of adaptation efforts and on the magnitude and pattern of future climate change. Individuals, communities, public health departments, health-related organizations and facilities, and others are taking action to reduce health vulnerability to current climate change and to increase resilience to the risks projected in coming decades.

The health benefits of reducing greenhouse gas emissions could result in economic benefits of hundreds of billions of dollars each year by the end of the century. Annual health impacts and health-related costs are projected to be approximately 50% lower under a lower scenario (RCP4.5) compared to a higher scenario (RCP8.5). These estimates would be even larger if they included the benefits of health outcomes that are difficult to quantify, such as avoided mental health impacts or long-term physical health impacts.

Vulnerable Populations



Examples of populations at higher risk of exposure to adverse climate-related health threats are shown along with adaptation measures that can help address disproportionate impacts. When considering the full range of threats from climate change as well as other environmental exposures, these groups are among the most exposed, most sensitive, and have the least individual and community resources to prepare for and respond to health threats. White text indicates the risks faced by those communities, while dark text indicates actions that can be taken to reduce those risks. *From Figure 14.2 (Source: EPA).*

A comprehensive assessment of the impacts of climate change on human health in the United States concluded that climate change exacerbates existing climate-sensitive health threats and creates new challenges, exposing more people in more places to hazardous weather and climate conditions.[1] This chapter builds on that assessment and considers the extent to which modifying current, or implementing new, health system responses could prepare for and manage these risks. Please see Chapter 13: Air Quality for a discussion of the health impacts associated with air quality, including ozone, wildfires, and aeroallergens.

Key Message 1

Climate Change Affects the Health of All Americans

The health and well-being of Americans are already affected by climate change, with the adverse health consequences projected to worsen with additional climate change. Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.

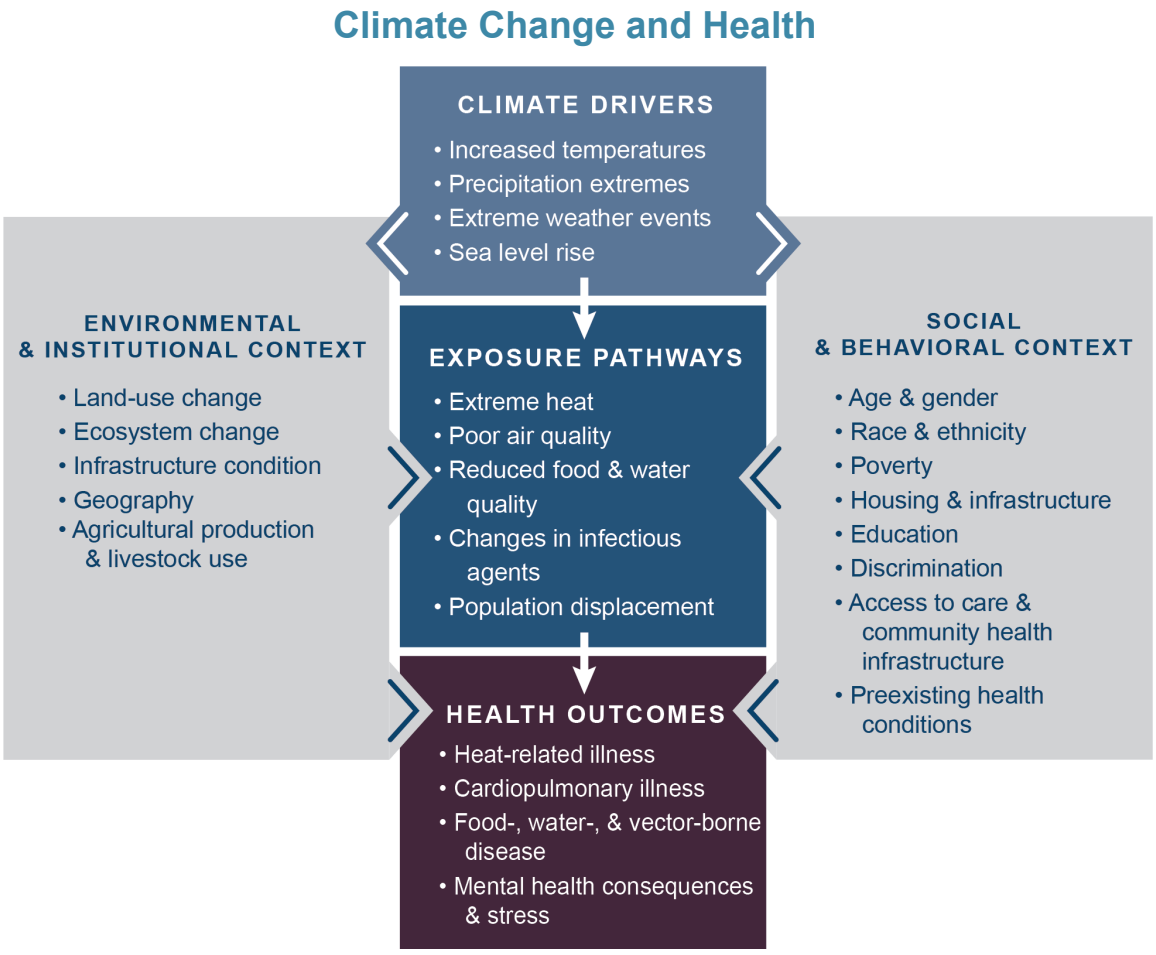


Figure 14.1: This conceptual diagram illustrates the exposure pathways by which climate change could affect human health. Exposure pathways exist within the context of other factors that positively or negatively influence health outcomes (gray side boxes). Key factors that influence vulnerability for individuals are shown in the right box and include social determinants of health and behavioral choices. Key factors that influence vulnerability at larger scales, such as natural and built environments, governance and management, and institutions, are shown in the left box. The extent to which climate change could alter the burden of disease in any location at any point in time will depend not just on the magnitude of local climate change but also on individual and population vulnerability, exposure to changing weather patterns, and capacity to manage risks, which may also be affected by climate change. Source: Balbus et al. 2016.[2]

The first paragraph in each of the following sections summarizes findings of the 2016 U.S. Climate and Health Assessment,[1] and the remainder of each section assesses findings from newly published research.

Extreme Events

More frequent and/or more intense extreme events, including drought, wildfires, heavy rainfall, floods, storms, and storm surge, are expected to adversely affect population health.[3] These events can exacerbate underlying medical conditions, increase stress, and lead to adverse mental health effects.[4] Further, extreme weather and climate events can disrupt critical public health, healthcare, and related systems in ways that can adversely affect health long after the event.[3]

Recent research improves identification of vulnerable population groups during and after an extreme event,[5] including their geographic location and needs (e.g. Bathi and Das 2016, Gotanda et al. 2015, Greenstein et al. 2016[6,7,8]). For example, the 2017 hurricane season highlighted the unique vulnerabilities of populations residing in Puerto Rico, the U.S. Virgin Islands, and other Caribbean islands (Ch. 20: U.S. Caribbean, Box 20.1).[9]

Temperature Extremes

High temperatures in the summer are conclusively linked to an increased risk of a range of illnesses and death, particularly among older adults, pregnant women, and children.[18] People living in urban areas may experience higher ambient temperatures because of the additional heat associated with urban heat islands, exacerbating heat-related risks.[19] With continued warming, increases in heat-related deaths are projected to outweigh reductions in cold-related deaths in most regions.[18]

Analyses of hospital admissions, emergency room visits, or emergency medical services calls show that hot days are associated with an increase in heat-related illnesses,[20,21] including cardiovascular and respiratory complications,[22]

Box 14.1: Health Impacts of Drought and Periods of Unusually Dry Months

In late 2015, California was in the fourth year of its most severe drought since becoming a state in 1850, with 63 emergency proclamations declared in cities, counties, tribal governments, and special districts.[10,11] Households in two drought-stricken counties (Tulare and Mariposa) reported a range of drought-related health impacts, including increased dust leading to allergies, asthma, and other respiratory issues and acute stress and diminished peace of mind.[10] These health effects were not evenly distributed, with more negative physical and mental health impacts reported when drought negatively affected household property and finances.

Drier conditions can increase reproduction of a fungus found in soils, potentially leading to the disease coccidioidomycosis, or Valley fever.[3,12] Coccidioidomycosis can cause persistent flu-like symptoms, with over 40% of cases hospitalized and 75% of patients unable to perform their normal daily activities for weeks, months, or longer. Higher numbers of cases in Arizona and California are associated with periods of drier conditions as measured by lower soil moisture in the previous winter and spring.[13]

Overall, the impacts of drought on hospital admissions and deaths depend on drought severity and the history of droughts in a region.[14] Complex relationships between drought and its associated economic consequences, particularly the interactions among factors that affect vulnerability, protective factors, and coping mechanisms, can increase mood disorders, domestic violence, and suicide.[15,16,17]

renal failure,[23] electrolyte imbalance, kidney stones,[24] negative impacts on fetal health,[25] and preterm birth.[26] Risks vary across regions (Ch. 18: Northeast, Box 18.3).[27] Health risks may be higher earlier in the summer season when populations are less accustomed to experiencing elevated temperatures, and different outcomes are observed at different levels of high temperature.[28,29] See Chapter 13: Air Quality for a discussion of the associations between temperature, air quality, and adverse health outcomes.

Vector-Borne Diseases

Climate change is expected to alter the geographic range, seasonal distribution, and abundance of disease vectors, exposing more people in North America to ticks that carry Lyme disease or other bacterial and viral agents, and to mosquitoes that transmit West Nile, chikungunya, dengue, and Zika viruses.[30,31,32] Changing weather patterns interact with other factors, including how pathogens adapt and change, changing ecosystems and land use, demographics, human behavior, and the status of public health infrastructure and management.[33,34]

El Niño events and other episodes of variable weather patterns may indicate the extent to which the risk of infectious disease transmission could increase with additional climate change.[33,35,36]

Increased temperatures and more frequent and intense extreme precipitation events can create conditions that favor the movement of vector-borne diseases into new geographic regions (e.g., Belova et al. 2017, Monaghan et al. 2016, Ogden and Lindsay 2016[31,37,38]). At the same time, very high temperatures may reduce transmission risk for some diseases.[39,40] Economic development also may substantially reduce transmission risk by reducing contacts with vector populations.[41] In the absence of adaptation, exposure to the mosquito *Aedes aegypti*, which can transmit dengue, Zika, chikungunya, and yellow fever viruses, is projected to increase by the end of the century due to climatic, demographic, and socioeconomic changes, with some of the largest increases projected to occur in North America.[31,32] Similarly, changes in temperature may influence the distribution and abundance of tick species that transmit common pathogens.[38,42,43]

Box 14.2: Transboundary Transmission of Infectious Diseases

Outbreaks occurring in other countries can impact U.S. populations and military personnel living abroad and can sometimes affect the United States. For example, the 2015–2016 El Niño, one of the strongest on record,[44] may have contributed to the 2014–2016 Zika epidemic in the Americas.[31,45,46,47,48] Warmer conditions may have facilitated expansion of the geographic range of mosquito populations and increased their capacity to transmit Zika virus.[40] Zika virus can cause a wide range of symptoms, including fever, rash, and headaches, as well as birth defects. The outbreak began in South America and spread to areas with mosquitoes capable of transmitting the virus, including Puerto Rico, the U.S. Virgin Islands, Florida, and Texas.

Water-Related Illnesses and Death

Increasing water temperatures associated with climate change are projected to alter the seasonality of growth and the geographic range of harmful algae and coastal pathogens, and runoff from more frequent and intense rainfall is projected to increasingly compromise recreational waters and sources of drinking water through increased introductions of pathogens and toxic algal blooms.[49,50,51,52,53,54]

Projected increases in extreme precipitation and flooding, combined with inadequate water and sewer infrastructure, can contribute to viral and bacterial contamination from

combined sewage overflows and a lack of access to potable drinking water, increasing exposure to pathogens that lead to gastrointestinal illness.[55,56,57,58,59] The relationship between precipitation and temperature-driven transmission of waterborne diseases is complex and site-specific, with, for example, some areas finding increased numbers of cases associated with excessive rainfall and others finding stronger associations with drought.[60,61,62,63,64,65] Heavy rainfall, flooding, and high temperatures have been linked to increases in diarrheal disease[62,64,66,67] and can increase other bacterial and parasitic infections such as leptospirosis and cryptosporidiosis.[65,68] Increases in air temperatures and heat waves are expected to increase temperature-sensitive marine pathogens such as *Vibrio*.[60,69,70,71]

Food Safety and Nutrition

Climate change, including rising temperatures and changes in weather extremes, is projected to adversely affect food security by altering exposures to certain pathogens and toxins (for example, *Salmonella*, *Campylobacter*, *Vibrio parahaemolyticus* in raw oysters, and mycotoxigenic fungi).[72]

Climate change, including changes in some extreme weather and climate events, can adversely affect global and U.S. food security by, for example, threatening food safety,[73,74,75] disrupting food availability, decreasing access to food, and increasing food prices.[76,77,78,79,80,81,82] Food quality also is expected to be affected by rising CO_2 concentrations that decrease dietary iron,[83] zinc,[84] protein,[85] and other macro- and micronutrients in crops[86,87,88] and seafood.[89,90] Projected changes in carbon dioxide concentrations and climate change could diminish expected gains in global nutrition; however, any impact on human health will depend on the many other drivers of global food security and factors such as food chain management, human behavior, and food safety governance.[91,92,93,94]

Mental Health

Mental health consequences, ranging from minimal stress and distress symptoms to clinical disorders, such as anxiety, depression, post-traumatic stress, and suicidality, can result from exposures to short-lived or prolonged climate- or weather-related events and their health consequences.[4] These mental health impacts can interact with other health, social, and environmental stressors to diminish an individual's well-being. Some groups are more vulnerable than others, including the elderly, pregnant women, people with preexisting mental illness, the economically disadvantaged, tribal and Indigenous communities, and first responders.[4]

Individuals whose households experienced a flood or risk of flood report higher levels of depression and anxiety, and these impacts can persist several years after the event.[95,96,97,98] Disasters present a heavy burden on the mental health of children when there is forced displacement from their home or a loss of family and community stability.[99] Increased use of alcohol and tobacco are common following disasters as well as droughts.[15,16,100,101] Higher temperatures can lead to an increase in aggressive behaviors, including homicide.[102,103] Social cohesion, good coping skills, and preemptive disaster planning are examples of adaptive measures that can help reduce the risk of prolonged psychological impacts.[102,104,105]

Key Message 2

Exposure and Resilience Vary Across Populations and Communities

People and communities are differentially exposed to hazards and disproportionately affected by climate-related health risks. Populations experiencing greater health risks include children, older adults, low-income communities, and some communities of color.

The health impacts of climate change are not felt equally, and some populations are at higher risk than others.[106] Low-income communities and some communities of color are often already overburdened with poor environmental conditions and are disproportionately affected by, and less resilient to, the health impacts of climate change.[106,107,108,109,110] The health risks of climate change are expected to compound existing health issues in Native American and Alaska Native communities, in part due to the loss of traditional foods and practices, the mental stress from permanent community displacement, increased injuries from lack of permafrost, storm damage and flooding, smoke inhalation, damage to water and sanitation systems, decreased food security, and new infectious diseases (Ch. 15: Tribes; Ch. 26: Alaska).[111,112]

Across all climate risks, children, older adults, low-income communities, some communities of color, and those experiencing discrimination are disproportionately affected by extreme weather and climate events, partially because they are often excluded in planning processes.[113] Other populations might experience increased climate risks due to a combination of exposure and sensitivity, such as outdoor workers, communities disproportionately burdened by poor environmental quality, and some communities in the rural Southeastern United States (Ch. 19: Southeast).[114,115,116]

Vulnerable Populations

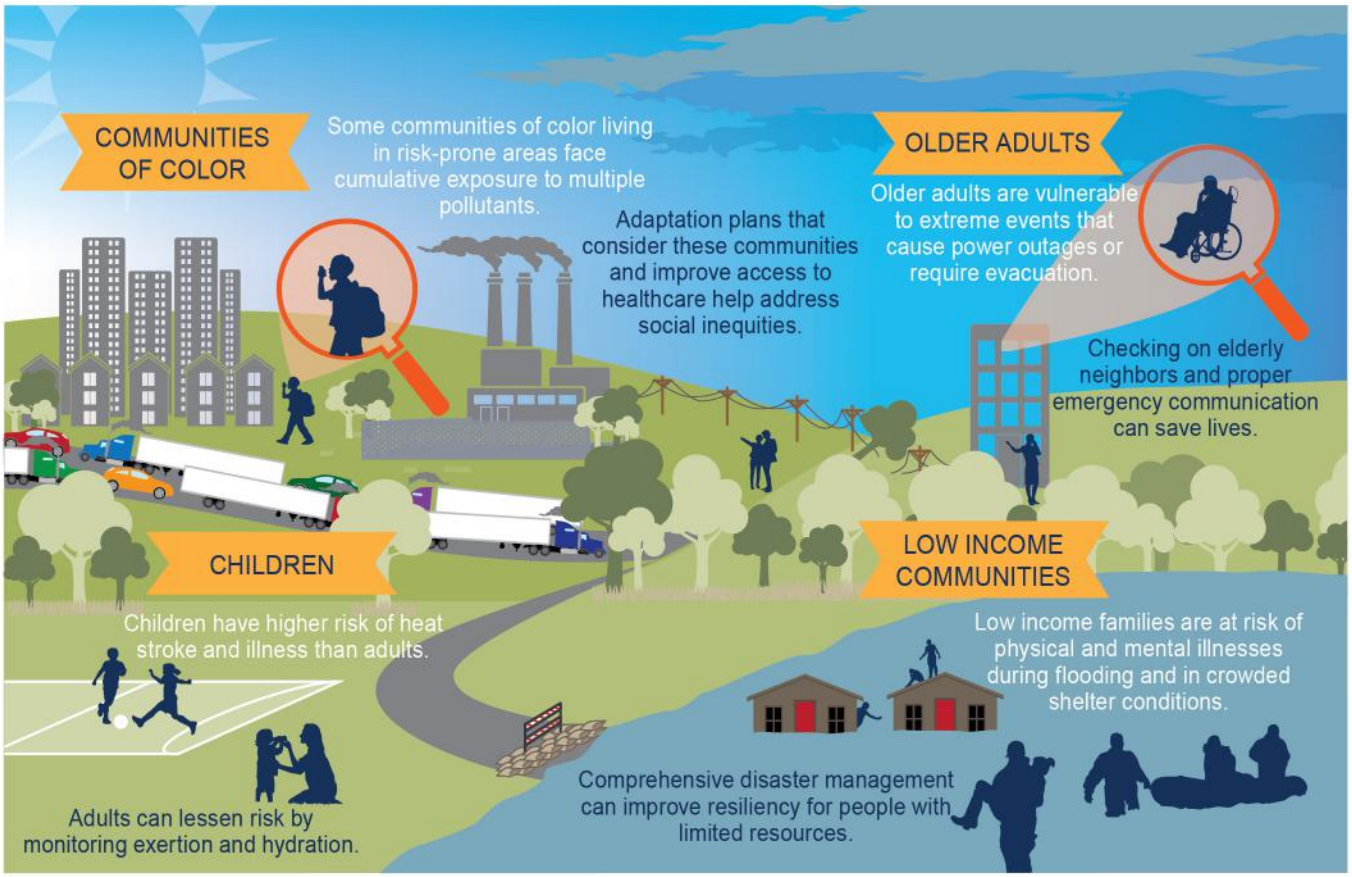


Figure 14.2: Examples of populations at higher risk of exposure to adverse climate-related health threats are shown along with adaptation measures that can help address disproportionate impacts. When considering the full range of threats from climate change as well as other environmental exposures, these groups are among the most exposed, most sensitive, and have the least individual and community resources to prepare for and respond to health threats. White text indicates the risks faced by those communities, while dark text indicates actions that can be taken to reduce those risks. Source: EPA.

Additional populations with increased health and social vulnerability typically have less access to information, resources, institutions, and other factors to prepare for and avoid the health risks of climate change. Some of these communities include poor people in high-income regions, minority groups, women, pregnant women, those experiencing discrimination, children under five, persons with physical and mental illness, persons with physical and cognitive disabilities, the homeless, those living alone, Indigenous people, people displaced because of weather and climate, the socially isolated, poorly planned communities, the disenfranchised, those with less access to healthcare, the uninsured and underinsured, those living in inadequate housing, and those with limited financial resources to rebound from disasters.[107,109,117,118] Figure 14.2 depicts some of the populations vulnerable to weather, climate, and climate change.

Building Resilient Communities

Projections of climate change-related changes in the incidence of adverse health outcomes, associated treatment costs, and health disparities can promote understanding of the ethical and human rights dimensions of climate change, including the disproportionate share of climate-related risk experienced by socially marginalized and poor populations. Such projections can also highlight options to increase population resilience.[119,120,121] The ability of a community to anticipate, plan for, and reduce impacts is enhanced when these efforts build on other environmental and social programs directed at sustainably and equitably addressing human needs.[122] Resilience is enhanced by community-driven planning processes where residents of vulnerable and impacted communities define for themselves the complex climate challenges they face and the climate solutions most relevant to their unique vulnerabilities.[110,123,124,125] A flood-related disaster in central Appalachia in spring 2013 highlighted how community-based coping strategies related to faith and spirituality, cultural values and heritage, and social support can enhance resilience post-disaster.[126]

Communities in Louisiana and New Jersey, for example, are already experiencing a host of negative environmental exposures coupled with extreme coastal and inland flooding. Language-appropriate educational campaigns can highlight the effectiveness of ecological protective measures (such as restoring marshes and dunes to prevent or reduce surge flooding) for increasing resilience. Resilience also can be built by creating institutional readiness, recognizing the importance of resident mobility (geographic movements at various scales such as commuting, migration, and evacuation), acknowledging the importance and support of social networks (such as family, church, and community), and facilitating adaptation to changing conditions.[127,128]

Key Message 3

Adaptation Reduces Risks and Improves Health

Proactive adaptation policies and programs reduce the risks and impacts from climate-sensitive health outcomes and from disruptions in healthcare services. Additional benefits to health arise from explicitly accounting for climate change risks in infrastructure planning and urban design.

Adapting to the Health Risks of Climate Change

Individuals, communities, public health departments, healthcare facilities, organizations, and others are taking action to reduce health and social vulnerabilities to current climate change and to increase resilience to the risks projected in coming decades.[129]

Examples of state-level adaptation actions include conducting vulnerability and adaptation assessments, developing comprehensive response plans (for example, extreme heat),[110,130] climate-proofing healthcare infrastructure, and implementing integrated surveillance of climate-sensitive infectious disease (for example, Lyme disease). Incorporating short-term to seasonal forecasts into public health programs and activities can protect population health today and under a warming climate.[129] Over decades or longer, emergency preparedness and disaster risk reduction planning can benefit from incorporating climate projections to ensure communities are prepared for changing weather patterns.[131]

Local efforts include altering urban design (for example, by using cool roofs, tree shades, and green walkways) and improving water management (for example, via desalination plants or watershed protection). These can provide health and social justice benefits, elicit neighborhood participation, and increase resilience for specific populations, such as outdoor workers.[107,132,133]

Adaptation options at multiple scales are needed to prepare for and manage health risks in a changing climate. For example, options to manage heat-related mortality include individual acclimatization (the process of adjusting to higher temperatures) as well as protective measures, such as heat wave early warnings,[134] air conditioning at home, cooling shelters,[135] green space in the neighborhood,[136,137] and resilient power grids to avoid power outages during extreme weather events.[138]

Early warning and response systems can protect population health now and provide a basis for more effective adaptation to future climate.[139,140,141] Improvements in forecasting weather and climate conditions and in environmental observation systems, in combination with social factors, can provide information on when and where changing weather patterns could result in increasing numbers of cases of, for example, heat stress or an infectious disease.[31,45,142,143,144] Such early warning systems can provide more time to pre-position resources and implement control programs, thereby preventing adverse health outcomes. For example, to help communities prepare for extreme heat, federal agencies are partnering with local entities to bring together stakeholders across the fields of public health, meteorology, emergency management, and policy to develop useful information systems that can prevent heat-related illnesses and deaths.[145] Adaptation efforts outside the health sector can have health benefits when, for example, infrastructure planning is designed to cool ambient temperatures and attenuate storm water runoff[146,147] and when interagency planning initiatives involve transportation, ecosystem management, urban planning, and water management.[148] Adaptation measures developed and deployed in other sectors can harm population health if they are developed and implemented without taking health into consideration.

Box 14.3: Healthcare

The U.S. healthcare sector is a significant contributor to climate change, accounting for about 10% of total U.S. greenhouse gas emissions.[149] Healthcare facilities are also a critical component of communities' emergency response system and resilience to climate change. Measures within healthcare institutions that decrease greenhouse gas emissions could significantly reduce U.S. emissions, reduce operating costs, and contribute to greater resilience of healthcare infrastructure. For example, U.S. hospitals could save roughly $15 billion over 10 years by adopting basic energy efficiency and waste-reduction measures (cumulative; no discount rate reported).[150] Combined heat and power systems can enhance hospitals' resilience in the face of interruptions to the power grid while reducing costs and emissions in normal operations.[151]

Box 14.3: Healthcare, continued

Hospitals at Risk from Storm Surge by Hurricanes

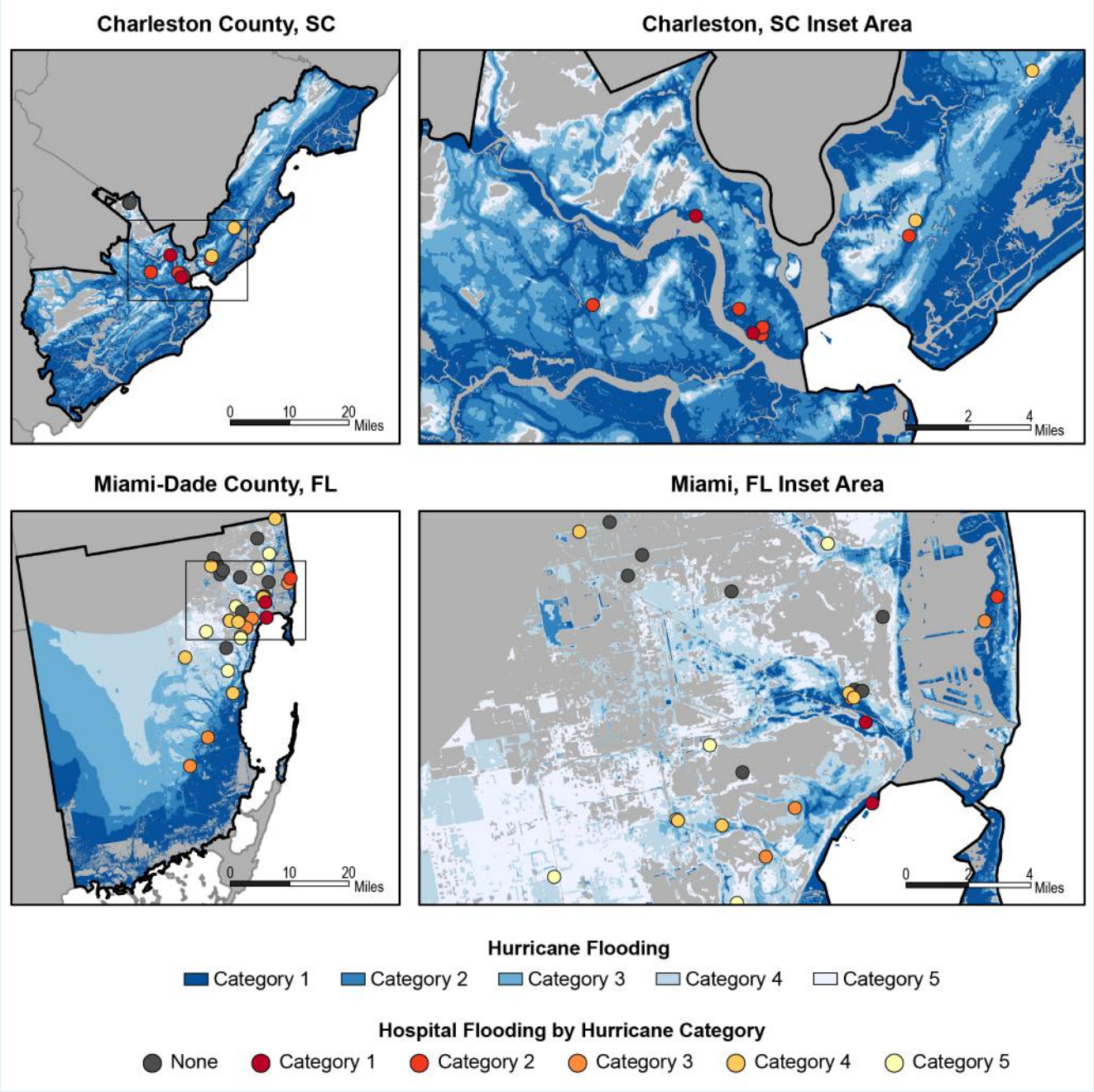


Figure 14.3: These maps show the locations of hospitals in (top) Charleston County, South Carolina, and (bottom) Miami-Dade County, Florida, with respect to storm surge inundation for different categories of hurricanes making landfall at high tide. Colors indicate the lowest category hurricane affecting a given location, with darker blue shading indicating areas with the greatest susceptibility to flooding and darker red dots indicating the most vulnerable hospitals. Four of the 38 (11%) hospitals in Miami-Dade County face possible storm surge inundation following a Category 2 hurricane; this could increase to 26 (68%) following a Category 5 hurricane. Charleston hospitals are more exposed to inundation risks. Seven of the 11 (64%) hospitals in Charleston County face possible storm surge inundation following a Category 2; this could increase to 9 (82%) following a Category 4. The impacts of a storm surge will depend on the effectiveness of resilience measures, such as flood walls, deployed by the facilities. Data from National Hurricane Center 2018[152] and the Department of Homeland Security 2018.[153]

Box 14.3: Healthcare, *continued*

In addition, healthcare facilities may benefit from modifications to prepare for potential consequences of climate change. For example, Nicklaus Children's Hospital, formerly Miami Children's, invested $11.3 million in a range of technology retrofits, including a hurricane-resistant shell, to withstand Category 4 hurricanes for uninterrupted, specialized medical care services.[151] The hospital was able to operate uninterrupted during Hurricane Irma and provided shelter for spouses and families of storm-duty staff and some storm evacuees. Assessment of climate change related risks to healthcare facilities and services can inform healthcare sector disaster preparedness efforts. For example, analyses in Los Angeles County suggest that preparing for increased wildfire risk should be a priority for area hospitals.[154]

Key Message 4

Reducing Greenhouse Gas Emissions Results in Health and Economic Benefits

Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term. By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions.

Reducing greenhouse gas emissions (Ch. 29: Mitigation) would benefit the health of Americans in the near and long term.[1,155] Adverse health effects attributed to climate change have many potential economic and social costs, including medical expenses, caregiving services, or lost productivity, as well as costs that are harder to quantify, such as those associated with pain, suffering, inconvenience, or reduced enjoyment of leisure activities.[156] These health burdens are typically borne by the affected individual as well as family, friends, employers, communities, and insurance or assistance programs.

Under a lower scenario (RCP4.5) by the end of this century, thousands of lives could be saved and hundreds of billions of dollars of health-related costs could be avoided compared to a higher scenario (RCP8.5).[157] Annual health impacts (including from temperature extremes, poor air quality, and vector-borne diseases) and health-related costs are projected to be approximately 50% less under a lower scenario (RCP4.5) than under a higher scenario (RCP8.5) (methods are summarized in Traceable Accounts) (see also Ch. 13: Air Quality).[37,157,158,159,160,161,162,163,164,165,166,167] The projected lives saved and economic benefits are likely to underestimate the true value because they do not include benefits of impacts that are difficult to quantify, such as mental health or long-term health impacts (see the Scenario Products Section in App. 3 for more on scenarios).

Temperature-Related Mortality

The projected increase in the annual number of heat wave days is substantially reduced under a lower scenario (RCP4.5) compared to a higher scenario (RCP8.5), reducing heat wave intensities[161,168] and resulting in fewer high-mortality heat waves[162,168] without considering adaptation (Figure 14.4). In 49 large cities in the United States, changes in extreme hot and extreme cold temperatures are projected to result in more than 9,000 additional premature deaths per year under a higher scenario by the end of the century, although this number would be lower if considering acclimatization or other adaptations (for example, increased use of air conditioning). Under a lower

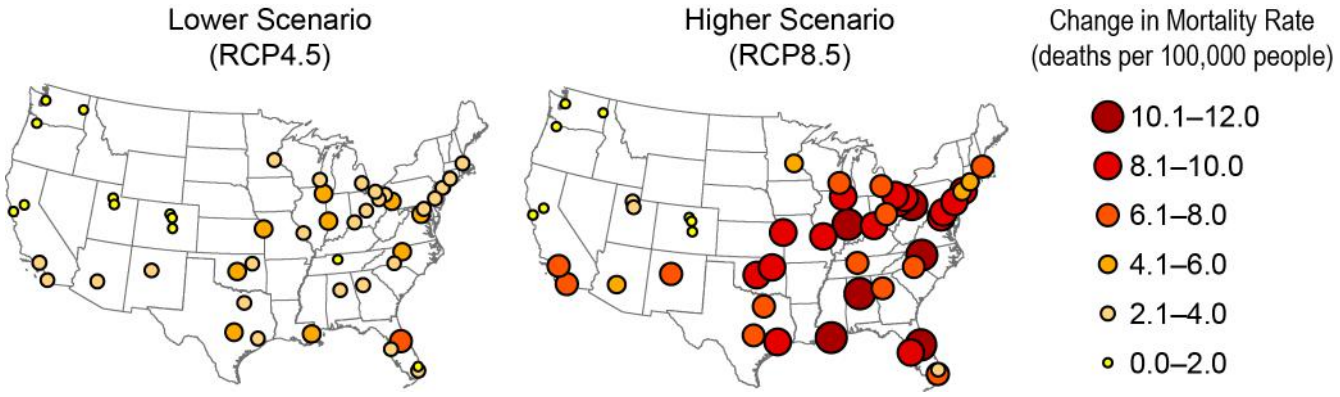


Figure 14.4: The maps show estimated changes in annual net mortality due to extremely hot and cold days in 49 U.S. cities for 2080–2099 as compared to 1989–2000. Across these cities, the change in mortality is projected to be an additional 9,300 deaths each year under a higher scenario (RCP8.5) and 3,900 deaths each year under a lower scenario (RCP4.5). Assuming a future in which the human health response to extreme temperatures in all 49 cities was equal to that of Dallas today (for example, as a result of availability of air conditioning or physiological adaptation) results in an approximate 50% reduction in these mortality estimates. For example, in Atlanta, an additional 349 people are projected to die from extreme temperatures each year by the end of century under RCP8.5. Assuming residents of Atlanta in 2090 have the adaptive capacity of Dallas residents today, this number is reduced to 128 additional deaths per year. Cities without circles should not be interpreted as having no extreme temperature impact. Data not available for the U.S. Caribbean, Alaska, or Hawai'i & U.S.-Affiliated Pacific Islands regions. Source: adapted from EPA 2017.[157]

scenario, more than half of these deaths could be avoided each year. Annual damages associated with the additional extreme temperature-related deaths in 2090 were projected to be $140 billion (in 2015 dollars) under a higher scenario (RCP8.5) and $60 billion under a lower scenario (RCP4.5).[157]

Labor Productivity

Under a higher scenario (RCP8.5), almost two billion labor hours are projected to be lost annually by 2090 from the impacts of temperature extremes, costing an estimated $160 billion in lost wages (in 2015 dollars) (Ch. 1: Overview, Figure 1.21).[157,167,169] States within the Southeast and Southern Great Plains regions are projected to experience higher impacts, with labor productivity in jobs with greater exposure to heat projected to decline by 3% (Ch. 19: Southeast).[164,170] Some counties in Texas and Florida are projected to experience more than 6% losses in annual labor hours by the end of the century.[157,160]

Infectious Diseases

Annual national cases of West Nile neuroinvasive disease are projected to more than double by 2050 due to increasing temperatures, among other factors,[30,171] resulting in approximately $1 billion per year in hospitalization costs and premature deaths under a higher scenario (RCP8.5; in 2015 dollars).[37] In this same scenario, an additional 3,300 cases and $3.3 billion in costs (in 2015 dollars) are projected each year by the end of the century. Approximately half of these cases and costs would be avoided under a lower scenario (RCP4.5).[37,157]

Water Quality

By the end of the century, warming under a higher scenario (RCP8.5) is projected to increase the length of time recreational waters have concentrations of harmful algal blooms (cyanobacteria) above the recommended public health threshold by one month annually; these bacteria can produce a range of toxins that can cause gastrointestinal illness, neurological disorders, and other illnesses.[157,165] The increase in the number of days where recreational waters pose this health risk is almost halved under a lower scenario (RCP4.5).

Acknowledgments

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Opening Image Credit

Algal bloom: NOAA Great Lakes Environmental Research Laboratory.

Traceable Accounts

Process Description

The chapter evaluated the scientific evidence of the health risks of climate change, focusing primarily on the literature published since the cutoff date (approximately fall 2015) of the U.S. Climate and Health Assessment.[1] A comprehensive literature search was performed by federal contractors in December 2016 for studies published since January 1, 2014, using PubMed, Scopus, and Web of Science. An Excel file containing 2,477 peer-reviewed studies was provided to the author team for it to consider in this assessment. In addition to the literature review, the authors considered recommended studies submitted in comments by the public, the National Academies of Sciences, Engineering, and Medicine, and federal agencies. The focus of the literature was on health risks in the United States, with limited citations from other countries providing insights into risks Americans are or will likely face with climate change. A full description of the search strategy can be found at https://www.niehs.nih.gov/CCHH_Search_Strategy_NCA4_508.pdf. The chapter authors were chosen based on their expertise in the health risks of climate change. Teleconferences were held with interested researchers and practitioners in climate change and health and with authors in other chapters of this Fourth National Climate Assessment (NCA4).

The U.S. Climate and Health Assessment[1] did not consider adaptation or mitigation, including economic costs and benefits, so the literature cited includes research from earlier years where additional information was relevant to this assessment.

For NCA4, Air Quality was added as a report chapter. Therefore, while Key Messages in this Health chapter include consideration of threats to human health from worsened air quality, the assessment of these risks and impacts are covered in Chapter 13: Air Quality. Similarly, co-benefits of reducing greenhouse gas emissions are covered in the Air Quality chapter.

Key Message 1

Climate Change Affects the Health of All Americans

The health and well-being of Americans are already affected by climate change (*very high confidence*), with the adverse health consequences projected to worsen with additional climate change (*likely, high confidence*). Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.

Description of evidence base

Multiple lines of evidence demonstrate statistically significant associations between temperature, precipitation, and other variables and adverse climate-sensitive health outcomes, indicating sensitivity to weather patterns.[1] These lines of evidence also demonstrate that vulnerability varies across sub-populations and geographic areas; populations with higher vulnerability include poor people in high-income regions, minority groups, women, children, the disabled, those living alone, those with poor health status, Indigenous people, older adults, outdoor workers, people displaced because of weather and climate, low-income residents that lack a social network, poorly planned

communities, communities disproportionately burdened by poor environmental quality, the disenfranchised, those with less access to healthcare, and those with limited financial resources to rebound from disasters.[108,109,110,111,118,172] Recent research confirms projections that the magnitude and pattern of risks are expected to increase as climate change continues across the century.[173]

Major uncertainties

The role of non-climate factors, including socioeconomic conditions, population characteristics, and human behavior, as well as health sector policies and practices, will continue to make it challenging to attribute injuries, illnesses, and deaths to climate change. Inadequate consideration of these factors creates uncertainties in projections of the magnitude and pattern of health risks over coming decades. Certainty is higher in near-term projections where there is greater understanding of future trends.

Description of confidence and likelihood

There is *very high confidence* that climate change is affecting the health of Americans. There is *high confidence* that climate-related health risks, without additional adaptation and mitigation, will *likely* increase with additional climate change.

Key Message 2

Exposure and Resilience Vary Across Populations and Communities

People and communities are differentially exposed to hazards and disproportionately affected by climate-related health risks (*high confidence*). Populations experiencing greater health risks include children, older adults, low-income communities, and some communities of color (*high confidence*).

Description of evidence base

Multiple lines of evidence demonstrate that low-income communities and some communities of color are experiencing higher rates of exposure to adverse environmental conditions and social conditions that can reduce their resilience to the impacts of climate change.[106,107,108,109,110] Populations with increased health and social vulnerability typically have less access to information, resources, institutions, and other factors to prepare for and avoid the health risks of climate change.[107,132,133] Across all climate-related health risks, children, older adults, low-income communities, and some communities of color are disproportionately impacted. There is high agreement among experts but fewer analyses demonstrating that other populations with increased vulnerability include outdoor workers, communities disproportionately burdened by poor environmental quality, communities in the rural southeastern United States, women, pregnant women, those experiencing gender discrimination, persons with chronic physical and mental illness, persons with various disabilities (such as those affecting mobility, long-term health, sensory perception, cognition), the homeless, those living alone, Indigenous people, people displaced because of weather and climate, low-income residents who lack a social network, poorly planned communities, the disenfranchised, those with less access to healthcare, the uninsured and underinsured,

those living in inadequate housing, and those with limited financial resources to rebound from disasters.[106,107,108,110,118]

Adaptation can increase the climate resilience of populations when the process of developing and implementing policies and measures includes understanding the ethical and human rights dimensions of climate change, meeting human needs in a sustainable and equitable way, and engaging with representatives of the most impacted communities to assess the challenges they face and to define the climate solutions.[124,125]

Major uncertainties

The role of non-climate factors, including socioeconomic conditions, discrimination (racial and ethnic, gender, persons with disabilities), psychosocial stressors, and the continued challenge to measure the cumulative effects of past, present, and future environmental exposures on certain people and communities will continue to make it challenging to attribute injuries, illnesses, and deaths to climate change. While there is no universal framework for building more resilient communities that can address the unique situations across the United States, factors integral to community resilience include the importance of social networks, the value of including community voice in the planning and execution of solutions, and the co-benefits of institutional readiness to address the physical, health, and social needs of impacted communities. These remain hard to quantify.[127,128]

Description of confidence and likelihood

There is *high confidence* that climate change is disproportionately affecting the health of children, older adults, low-income communities, communities of color, tribal and Indigenous communities, and many other distinct populations. And there is *high confidence* that some of the most vulnerable populations experience greater barriers to accessing resources, information, and tools to build resilience.

Key Message 3

Adaptation Reduces Risks and Improves Health

Proactive adaptation policies and programs reduce the risks and impacts from climate-sensitive health outcomes and from disruptions in healthcare services (*medium confidence*). Additional benefits to health arise from explicitly accounting for climate change risks in infrastructure planning and urban design (*low confidence*).

Description of evidence base

Health adaptation is taking place from local to national scales.[129,148,174] Because most of the health risks of climate change are also current public health problems, strengthening standard health system policies and programs, such as monitoring and surveillance, are expected to be effective in the short term in addressing the additional health risks of climate change. Modifications to explicitly incorporate climate change are important to ensure effectiveness as the climate continues to change. Incorporating environmentally friendly practices into healthcare and infrastructure can promote resilience.[151]

Major uncertainties

Overall, while there is considerable evidence of the effectiveness of public health programs,[110,129,130] the effectiveness of policies and programs to reduce *future* burdens of climate-sensitive health outcomes in a changing climate can only be determined over coming decades. The relatively short time period of implementing health adaptation programs means uncertainties remain about how to best incorporate climate change into existing policies and programs to manage climate-sensitive health outcomes and about which interventions will likely be most effective as the climate continues to change.[174,175] For example, heat wave early warning and response systems save lives, but it is not clear which components most effectively contribute to morbidity and mortality reduction.

Description of confidence and likelihood

There is *medium confidence* that with sufficient human and financial resources, adaptation policies and programs can reduce the current burden of climate-sensitive health outcomes.[110,151,176,177] There is *low confidence* that the incorporation of health risks into infrastructure and urban planning and design will likely decrease climate-sensitive health impacts.

Key Message 4

Reducing Greenhouse Gas Emissions Results in Health and Economic Benefits

Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term (*high confidence*). By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions (*likely, medium confidence*).

Description of evidence base

Benefits of mitigation associated with air quality, including co-benefits of reducing greenhouse gas emissions, can be found in Chapter 13: Air Quality. This Key Message is consistent with and inclusive of those findings.

Multiple individual lines of evidence across several health topic areas demonstrate significant benefits of greenhouse gas emission reductions, with health impacts and health-related costs reduced by approximately half under RCP4.5 compared to RCP8.5 by the end of the century, based on comprehensive multisector quantitative analyses of economic impacts projected under consistent scenarios (Ch. 13: Air Quality).[37,157,158,159,160,161,162,163,164,165,166,167] The economic benefits of greenhouse gas emissions reductions to the health sector could be on the order of hundreds of billions of dollars annually by the end of the century.

Heat: Greenhouse gas emission reductions under RCP4.5 could substantially reduce the annual number of heat wave days (for example, by 21 in the Northwest and by 43 in the Southeast by the end of the century);[161] the number of high-mortality heat waves;[162,168] and heat wave intensities.[161,168] The EPA (2017)[157] estimated city-specific relationships between daily deaths (from all causes) and extreme temperatures based on historical observations that were combined with the projections of extremely hot and cold days (average of three years centered on 2050 and 2090) using city-specific extreme temperature thresholds to project future deaths from extreme heat and cold

under RCP8.5 and RCP4.5 in five global climate models (GCMs). In 49 large U.S. cities, changes in extreme temperatures are projected to result in over 9,000 premature deaths per year under RCP8.5 by the end of the century without adaptation ($140 billion each year); under RCP4.5, more than half these deaths could be avoided annually ($60 billion each year).[157]

Labor productivity: Hsiang et al. (2017)[167] and the EPA (2017)[157] estimated the number of labor hours from changes in extreme temperatures using dose–response functions for the relationship between temperature and labor from Graff Zivin and Neidell (2014).[169] Under RCP8.5, almost 2 billion labor hours are projected to be lost annually by 2090 from the impacts of extreme heat and cold, costing an estimated $160 billion in lost wages. The Southeast[164,170] and Southern Plains are projected to experience high impacts, with labor productivity in high-risk sectors projected to decline by 3%. Some counties in Texas and Florida are projected to experience more than 6% losses in annual labor hours by the end of the century.[157,160]

Vector-borne disease: Belova et al. (2017)[37] and the EPA (2017)[157] define health impact functions from regional associations between temperatures and the probability of above-average West Nile neuroinvasive disease (WNND) incidence to estimate county-level expected WNND incidence rates for a 1995 reference period (1986–2005) and two future years (2050: 2040–2059 and 2090: 2080–2099) using temperature data from five GCMs. Annual national cases of WNND are projected to more than double by 2050 due to increasing temperatures, resulting in approximately $1 billion per year in hospitalization costs and premature deaths. In 2090, an additional 3,300 annual cases are projected under RCP8.5, with $3.3 billion per year in costs. Greenhouse gas emission reductions under RCP4.5 could avoid approximately half these cases and costs.

Water quality: Chapra et al. (2017)[165] and the EPA (2017)[157] evaluate the biophysical impacts of climate change on the occurrence of cyanobacterial harmful algal blooms in the contiguous United States using models that project rainfall runoff, water demand, water resources systems, water quality, and algal growth. In 2090, warming under RCP8.5 is projected to increase the length of time that recreational waters have concentrations of harmful algal blooms (cyanobacteria) above the recommended public health threshold by one month annually; greenhouse gas emissions under RCP4.5 could reduce this by two weeks.

Food safety and nutrition: There is limited evidence quantifying specific health outcomes or economic impacts of reduced food safety and nutrition.

Major uncertainties

While projections consistently indicate that changes in climate are expected to have negative health consequences, quantifying specific health outcomes (for example, number of cases, number of premature deaths) remains challenging, as noted in Key Message 1. Economic estimates only partially capture and monetize impacts across each health topic area, which means that damage costs are likely to be an undervaluation of the actual health impacts that would occur under any given scenario. Economic estimates in this chapter do not include costs to the healthcare system.

Description of confidence and likelihood

There is a *high confidence* that a reduction in greenhouse gas emissions would benefit the health of Americans. There is *medium confidence* that reduced greenhouse gas emissions under RCP4.5

compared to RCP8.5 will *likely* reduce lost labor hours by almost half and avoid thousands of premature deaths and illnesses projected each year from climate impacts on extreme heat, ozone and aeroallergen levels (Ch. 13: Air Quality), and West Nile neuroinvasive disease. There is *medium confidence* that the economic benefits of greenhouse gas emissions reductions in the health sector could *likely* be on the order of hundreds of billions of dollars each year by the end of the century. Including avoided or reduced benefits of risks that are difficult to quantify, such as mental health or long-term health consequences, would increase these estimates.

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15 Tribes and Indigenous Peoples

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On the Web: https://nca2018.globalchange.gov/chapter/tribes

15 Tribes and Indigenous Peoples

Wind River Indian Reservation students collect seeds for a land restoration project.

Key Message 1

Indigenous Livelihoods and Economies at Risk

Climate change threatens Indigenous peoples' livelihoods and economies, including agriculture, hunting and gathering, fishing, forestry, energy, recreation, and tourism enterprises. Indigenous peoples' economies rely on, but face institutional barriers to, their self-determined management of water, land, other natural resources, and infrastructure that will be impacted increasingly by changes in climate.

Key Message 2

Physical, Mental, and Indigenous Values-Based Health at Risk

Indigenous health is based on interconnected social and ecological systems that are being disrupted by a changing climate. As these changes continue, the health of individuals and communities will be uniquely challenged by climate impacts to lands, waters, foods, and other plant and animal species. These impacts threaten sites, practices, and relationships with cultural, spiritual, or ceremonial importance that are foundational to Indigenous peoples' cultural heritages, identities, and physical and mental health.

Key Message 3

Adaptation, Disaster Management, Displacement, and Community-Led Relocations

Many Indigenous peoples have been proactively identifying and addressing climate impacts; however, institutional barriers exist in the United States that severely limit their adaptive capacities. These barriers include limited access to traditional territory and resources and the limitations of existing policies, programs, and funding mechanisms in accounting for the unique conditions of Indigenous communities. Successful adaptation in Indigenous contexts relies on use of Indigenous knowledge, resilient and robust social systems and protocols, a commitment to principles of self-determination, and proactive efforts on the part of federal, state, and local governments to alleviate institutional barriers.

Executive Summary

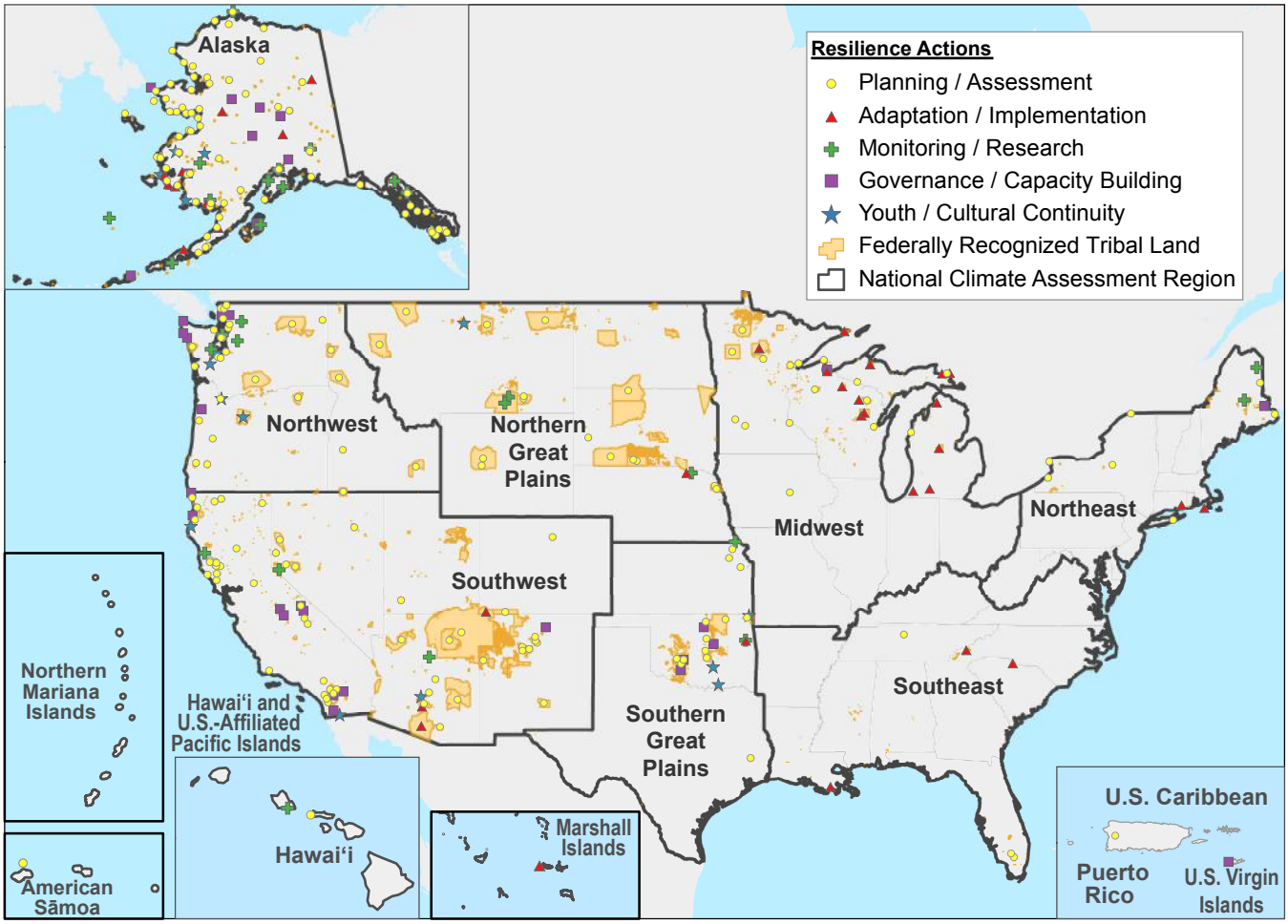
Indigenous peoples in the United States are diverse and distinct political and cultural groups and populations. Though they may be affected by climate change in ways that are similar to others in the United States, Indigenous peoples can also be affected uniquely and disproportionately. Many Indigenous peoples have lived in particular areas for hundreds if not thousands of years. Indigenous peoples' histories and shared experience engender distinct knowledge about climate change impacts and strategies for adaptation. Indigenous peoples' traditional knowledge systems can play a role in advancing understanding of climate change and in developing more comprehensive climate adaptation strategies.

Observed and projected changes of increased wildfire, diminished snowpack, pervasive drought, flooding, ocean acidification, and sea level rise threaten the viability of Indigenous peoples' traditional subsistence and commercial activities that include agriculture, hunting and gathering, fisheries, forestry, energy, recreation, and tourism enterprises. Despite institutional barriers to tribal self-determination stemming from federal trust authority over tribal trust lands, a number of tribes have adaptation plans that include a focus on subsistence and commercial economic activities. Some tribes are also pursuing climate mitigation actions through the development of renewable energy on tribal lands.

Climate impacts to lands, waters, foods, and other plant and animal species threaten cultural heritage sites and practices that sustain intra- and intergenerational relationships built on sharing traditional knowledges, food, and ceremonial or cultural objects. This weakens place-based cultural identities, may worsen historical trauma still experienced by many Indigenous peoples in the United States, and adversely affects mental health and Indigenous values-based understandings of health.

Throughout the United States, climate-related disasters are causing Indigenous communities to consider or actively pursue relocation as an adaptation strategy. Challenges to Indigenous actions to address disaster management and recovery, displacement, and relocation in the face of climate change include economic, social, political, and legal considerations that severely constrain their abilities to respond to rapid ecological shifts and complicate action toward safe and self-determined futures for these communities.

Indigenous Peoples' Climate Initiatives and Plans



Many Indigenous peoples are taking steps to adapt to climate change impacts. Search the online version of this map by activity type, region, and sector to find more information and links to each project: https://biamaps.doi.gov/nca/. To provide feedback and add new projects for inclusion in the database, see: https://www.bia.gov/bia/ots/tribal-resilience-program/nca/. Thus far, tribal entities in the Northwest have the highest concentration of climate activities (Ch. 24: Northwest). For other case studies of selected tribal adaptation activities, see both the Institute for Tribal Environmental Professionals' Tribal Profiles,[1] and Tribal Case Studies within the U.S. Climate Resilience Toolkit.[2,3] *From Figure 15.1 (Source: Bureau of Indian Affairs).*

State of the Sector

Indigenous peoples in the United States are diverse and distinct political and cultural groups and populations. Though they may be affected by climate change in ways that are similar to others in the United States, Indigenous peoples can also be affected uniquely and disproportionately. Many Indigenous peoples have lived in particular areas for hundreds if not thousands of years, and their cultures, spiritual practices, and economies have evolved to be adaptive to local seasonal and interannual environmental changes.[4] Thus, Indigenous knowledge systems differ from those of non-Indigenous peoples who colonized and settled the United States, and they engender distinct knowledge about climate change impacts and strategies for adaptation.[4,5,6] Indigenous knowledges, accumulated over generations through direct contact with the environment, broadly refer to Indigenous peoples' systems of observing, monitoring, researching, recording, communicating, and learning and their social adaptive capacity to adjust to or prepare for changes. One of these knowledge systems that is often referred to in the context of climate change is traditional ecological knowledge, which primarily focuses on the relationships between humans, plants, animals, natural phenomena, and the landscape.

A growing number of tribal governments and intertribal organizations are developing climate adaptation plans, with some in the early stages of implementation. Many Indigenous peoples support their own technical staff who study and manage broad sectoral programs and issues, which now include climate change adaptation planning and implementation. To this end, Indigenous peoples regularly collaborate with climate scientists and other professionals working in academic, governmental, and nongovernmental organizations, especially in the use of downscaled (local-scale) climate information and tools that have become more available in recent years. While not comprehensive, Figure 15.1 identifies over 800 activities across all regions featured in this report that Indigenous peoples and their partners have undertaken in the last decade. This map catalogues several broad types of adaptation projects: planning and assessment, adaptation and implementation, monitoring and research, governance and capacity building, and youth engagement and cultural continuity. Collectively, these activities span many sectors and all regions of the country. Projects are primarily planning related and include adaptation planning, vulnerability assessments, and professional development to increase the skills and capacity of tribal staff and management.

These actions in response to climate change occur in a broader context in which Indigenous peoples today, including federally and non-federally recognized tribes, are continuing to seek and exercise self-determination to define their own political status and to freely pursue economic, social, and cultural development. Limits to Indigenous self-determined action can intensify vulnerability to climate change in many cases. In the 19th century, the United States established a trust responsibility to federally recognized tribes, which is a legal and fiduciary obligation to honor their treaty rights and support tribal self-determination. The trust responsibility is meant to include financial support and the provision of essential services, such as education, health, public safety, and environmental protection. However, trust responsibility also authorizes the U.S. Government to manage tribal lands and the revenues generated from these lands. This can limit self-determination in cases where the U.S. Government's management of tribes' trust assets lacks accountability or does not adequately fulfill the federal policy requirement of consultation with tribes on a sovereign government-to-government basis.

Indigenous Peoples' Climate Initiatives and Plans

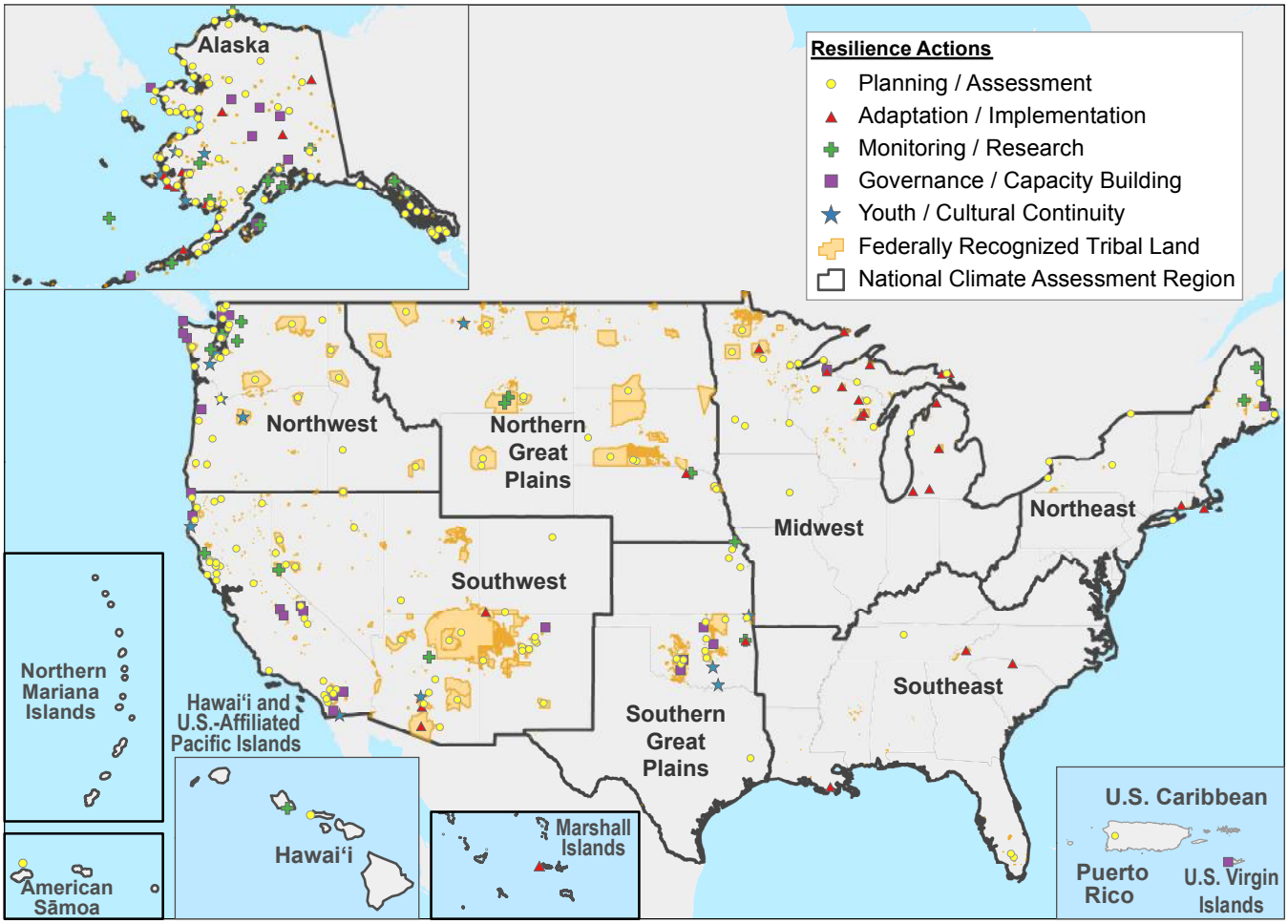


Figure 15.1: Many Indigenous peoples are taking steps to adapt to climate change impacts. Search the online version of this map by activity type, region, and sector to find more information and links to each project: https://biamaps.doi.gov/nca/. To provide feedback and add new projects for inclusion in the database, see: https://www.bia.gov/bia/ots/tribal-resilience-program/nca/. Thus far, tribal entities in the Northwest have the highest concentration of climate activities (Ch. 24: Northwest). For other case studies of tribal adaptation activities, see both the Institute for Tribal Environmental Professionals' Tribal Profiles,[1] and Tribal Case Studies within the U.S. Climate Resilience Toolkit.[2,3] Source: Bureau of Indian Affairs.

Non-federally recognized tribes, Native Hawaiians, and other Indigenous peoples also have rights to self-determination to protect their traditional knowledges, cultures, and ancestral lands, while developing their economies and providing community services; but they do so without reservation lands, treaty rights, and federal provision of essential services, among other rights, authorities, and capacities to which federally recognized tribes can appeal.

This chapter expands on the Indigenous Peoples chapter from the Third National Climate Assessment[7] and on Indigenous contributions to earlier assessments, with a focus on three major themes as expressed in the Key Messages that were not discussed in previous assessments in as much detail. This chapter recognizes that Indigenous communities of the United States represent diverse cultures, histories, governments, and environments and that their individual experiences with climate change will differ. In addition, this chapter attempts to provide more information than previous assessments about Indigenous issues in the Pacific Islands and the Caribbean regions, although in some cases, especially for the Caribbean, the literature is sparse. Thus, uniform, national-scale quantitative metrics of

risk across this broad spectrum of conditions are not available. Nevertheless, Indigenous peoples and their partners are building comprehensive understandings of local climate change risks and taking steps to adapt to these threats.

Key Message 1

Indigenous Livelihoods and Economies at Risk

Climate change threatens Indigenous peoples' livelihoods and economies, including agriculture, hunting and gathering, fishing, forestry, energy, recreation, and tourism enterprises. Indigenous peoples' economies rely on, but face institutional barriers to, their self-determined management of water, land, other natural resources, and infrastructure that will be impacted increasingly by changes in climate.

While the lands, waters, and other natural resources of Indigenous peoples hold sacred cultural significance, they also play a principal role in ensuring the viability of these communities' economies and livelihoods.[5,8] Tribal trust lands provide habitat for more than 525 species listed under the Endangered Species Act, and more than 13,000 miles of rivers and 997,000 lakes are located on federally recognized tribal lands.[9] For many tribes, despite this endowment of natural resources, median household income is only 69% of the national average median income.[10] Challenges to economic development for federally recognized tribes are in part related to institutional barriers to tribal self-determination stemming from federal trust authority over tribal trust lands.[8,11] Due to past federal polices, including the Dawes Act (1887) and Indian Reorganization Act (1934), most reservation lands today constitute a checkerboard pattern of trust and fee-simple (private) land ownership, highly fractionated government trust lands with many owners, and trust lands subject to ongoing federal oversight in resource management decisions.[12,13,14,15] These issues are complicated further when multiple or overlapping federal, state, or local government jurisdictions are involved.[16]

Historical and ongoing federal oversight of natural resource management on tribal lands can, in some cases, hinder growth in tribal and individual natural resource-based business enterprises, because tribes lack the autonomy to determine their own property rights and related institutions.[17,18] Similar critiques of historic and contemporary U.S. policy have been identified in studies of Indigenous climate change adaptation.[19,20] Non-federally recognized tribes lack legal status to qualify for federal funding and economic development support, though some are eligible for state support.[21] Funding limitations are often identified as a barrier to the planning or implementation of climate adaptation or mitigation actions,[22] which suggests that increased economic revenues could create opportunities for tribes to choose to pursue climate actions.

Many Indigenous peoples continue to express their cultural relationships with ancestral lands through traditional subsistence economies. Such economies rely on local natural resources for personal use (such as food, shelter, fuel, clothing, tools, transportation, and arts and crafts) and for trade, barter, or sharing. Climate change threatens these delicately balanced subsistence networks by, for example, changing the patterns of seasonal timing and availability of culturally important species in traditional hunting, gathering, and fishing areas[4,5,7,22,23,24,25,26,27,28,29,30,31,32] Each of the Fourth National Climate Assessment's regional chapters includes at least one example of climate impacts or adaptation related to Indigenous subsistence species or practices.

Most Indigenous peoples across all regions of the United States pursue a mix of traditional subsistence and commercial sector activities that include agriculture, hunting and gathering, fisheries, forestry, energy, recreation, and tourism enterprises.[5,22,33,34,35] Observed and projected changes of increased wildfire, diminished snowpack, pervasive drought, flooding, ocean acidification, and sea level rise (Ch. 2: Climate) threaten the viability of each of these enterprises.[22,29,33,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52] Tribal casino properties, for example, often include water-dependent recreational amenities that, due to pervasive drought, are impacted by changes to local water regimes,[53] and some tribes account for this in their adaptation plans, such as the Confederated Salish and Kootenai Tribes[54] and the Lummi Nation.[55] In addition, Indigenous agriculture is already being adversely affected by changing patterns of flooding, drought, dust storms, and rising temperatures, with future projections varying by region but indicating increased soil erosion and irrigation water demand and decreased crop quality and animal herd sizes (Ch. 25: Southwest, KM 4 and 6).[22,41,52,56,57,58] Some tribes include consideration of subsistence and commercial economic resources in their adaptation plans. For example, the 1854 Treaty Authority Adaptation Plan,[59] which includes the Bois Forte, Fond du Lac, and Grand Portage Tribes, provides detailed adaptation strategies customized to protect and sustain walleye, sturgeon, moose, and wild rice, among others (Ch. 21: Midwest). Similarly, the Confederated Tribes of the Umatilla Indian Reservation[60] have identified climate risks to salmon, elk, deer, roots, and huckleberry habitat (Ch. 24: Northwest, KM 2).

Federal and state legal frameworks and regulatory actions can compound physical climate change stressors on Indigenous peoples' subsistence economies and act as a barrier to climate change adaptation. For example, federal and state fish and wildlife regulations, such as endangered species listings, are meant to respond to species

Members of the Oglala Lakota Nation plant climate-resilient tree species on the Pine Ridge Indian Reservation in South Dakota. Photo credit: © Alex Basaraba (www.alexbasaraba.com).

population declines that can be exacerbated by climate change (Ch. 7: Ecosystems), but they can further stress Indigenous subsistence economies that have traditionally relied on those species.[61,62,63] Such regulatory actions taken without the input of Indigenous peoples can limit traditional sources of income, such as arts and crafts that are part of Indigenous economies. For example, some Alaska Natives utilize skins, furs, and walrus tusks to support local subsistence economies and to produce clothing and crafts that support local tourism.[64,65]

Another recognized barrier to economic self-determination and climate adaptation for federally recognized tribes with resource constraints is the costly and lengthy process to quantify, secure, and use appropriated water rights.[7,41,53,66,67,68] This is particularly the case in the arid western United States, where the majority of reservation land acreage is located and where prior appropriation doctrine is the primary mechanism for allocating scarce water resources.[66] As water becomes more scarce and regional demands increase, the quantification of water rights is viewed by many as necessary to design and plan adaptation strategies that secure water for various uses: cultural, municipal, recreational, agricultural, fisheries, and aquatic resources, among others.[4,19,58,66,67,69,70,71] To date, approximately 30 reservations have

engaged in water rights settlements,[72] and while research shows that water rights quantification can positively affect tribal economies, additional analysis is necessary to better understand these effects.[66]

Infrastructure and linked systems that support Indigenous economies and livelihoods are at risk from more frequent or intense heavy downpours, floods, heat waves, wildfires, and droughts, as well as higher sea levels and storm surges.[19,49,73] As shown in Figure 15.2, Indigenous peoples are vulnerable to infrastructure disruptions that can occur at the level of an individual household (for example, housing and sanitary water supply); within larger regional, integrated systems (such as for power, transportation, and telecommunication) (Ch. 17: Complex Systems); or within human systems that rely on such infrastructure to provide other essential services (such as emergency medical response). This vulnerability is partly due to long-standing, unmet infrastructure needs and deferred maintenance challenges.[74] For example, many Indigenous communities lack sufficient water delivery and treatment facilities and the operating capital needed to maintain and/or improve those facilities.[41,75,76]

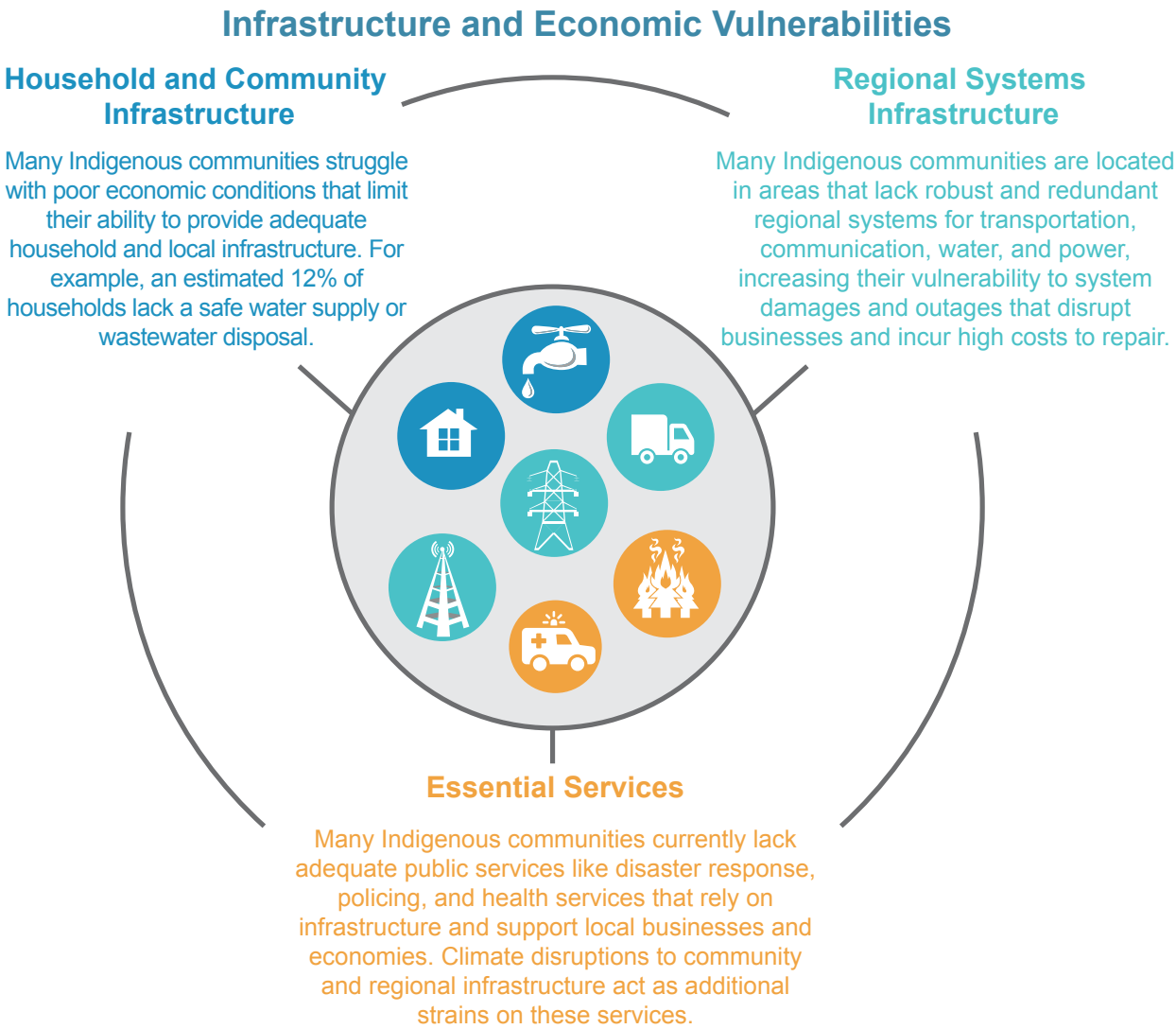


Figure 15.2: Communities' economic potential and livelihoods rely on infrastructure and the essential services it delivers, and many tribes and Indigenous communities already face acute infrastructure challenges that make them highly vulnerable to climate impacts.[22] Indigenous peoples along the coasts and in the islands, the Southwest, and Alaska have experienced the most extensive infrastructure-related impacts thus far (Ch. 8: Coastal; Ch. 20: U.S. Caribbean; Ch. 25: Southwest; Ch. 26: Alaska; Ch. 27: Hawai'i & Pacific Islands). Source: USGCRP.

Indigenous peoples also have unmet needs and challenges in the energy sector. The evolution of the federal trust doctrine, and its associated timely and costly regulatory oversight of resource use on tribal trust lands, challenges federally recognized tribes' ability to secure outside investments in energy and related infrastructure development (Ch. 4: Energy, KM 3; Ch. 29: Mitigation).[77,78] In addition, non-tribal entities operate the majority of energy development on tribal land, reducing opportunities for tribal workforce development and capacity building for self-directing future energy projects.[79] Still, energy development, particularly renewable energy, that is implemented in accordance with Indigenous values holds promise as a source of revenue, employment, and economic self-determination.[22,80] While not all Indigenous communities support energy development due to concerns about cultural and environmental impacts, there are a number of examples of growing interest in renewable energy.[79] The Pueblo of Jemez, for example, has developed the Nation's first utility-scale solar project on tribal lands, and other tribes view renewable energy as a key strategy for climate mitigation.[22] Tribes have also identified small-scale distributed electricity generation systems and energy efficiency as supporting their climate adaptation goals through increased energy independence.[22,79]

Key Message 2

Physical, Mental, and Indigenous Values-Based Health at Risk

Indigenous health is based on interconnected social and ecological systems that are being disrupted by a changing climate. As these changes continue, the health of individuals and communities will be uniquely challenged by climate impacts to lands, waters, foods, and other plant and animal species. These impacts threaten sites, practices, and relationships with cultural, spiritual, or ceremonial importance that are foundational to Indigenous peoples' cultural heritages, identities, and physical and mental health.

Physical health risks and impacts to Indigenous peoples are the same as those faced by the general U.S. population (Ch. 14: Human Health); however, certain factors, known as the social determinants of health, are unique and contribute to the increased vulnerability of Indigenous peoples to adverse and potentially severe or fatal health outcomes (Box 15.1). Conventional Western science approaches to measuring and analyzing Indigenous health, adaptive capacity, health disparities, and environmental justice issues typically do not capture many of the key elements of health and resilience that are important to Indigenous populations.[81,82,83,84,85,86] These elements emphasize non-physiological aspects of health, which include concepts related to community connection, natural resources security, cultural use, education and knowledge, self-determination and autonomy, and resilience.[83,84] For example, the Swinomish Indian Tribal Community has used shellfish beds and shoreline armoring as indicators to evaluate health in the context of a changing climate.[81]

Box 15.1: Social Determinants of Indigenous Health

A number of health risks are higher among Indigenous populations due in part to historic and contemporary social, political, and economic factors that can affect conditions of daily life and limit resources and opportunities for leading a healthy life.[87] Many Indigenous peoples still experience historical trauma associated with colonization, removal from their homelands, and loss of their traditional ways of life, and this has been identified as a contributor to contemporary physical and mental health impacts.[88,89] Other factors include institutional racism, living and working circumstances that increase exposure to health threats, and limited access to healthcare services.[87,89] Though local trends may differ across the country, in general, Indigenous peoples have disproportionately higher rates of asthma,[90] cardiovascular disease,[91,92,93,94] Alzheimer's disease or dementia,[95,96] diabetes,[97] and obesity.[93] These health disparities have direct linkages to increased vulnerability to climate change impacts, including changes in the pollen season and allergenicity, air quality, and extreme weather events (Ch. 14: Human Health).[98] For example, diabetes prevalence within federally recognized tribes is about twice that of the general U.S. population.[97] People with diabetes are more sensitive to extreme heat and air pollution, and physical health impacts can also influence mental health.[9]

Indigenous peoples have a unique and interconnected relationship with the natural environment that is integral to their place-based social, cultural, and spiritual identity; intangible cultural heritage (traditions or living expressions transmitted and inherited through generations); and subsistence practices and livelihoods.[61,82,87,99,100] Climate change impacts to ecosystems (Ch. 7: Ecosystems) alter the relationships between humans and animals, between individuals, and within and between communities; these relationships are central to Indigenous physical, mental, and spiritual health.[82,86,101,102] This alteration in relationships occurs when individuals, families, and communities (within and between generations) are less able or not able to share traditional knowledges about the natural environment (such as where and when to harvest or hunt), food, and ceremonial or cultural objects, among other things, because the knowledge is no longer accurate or traditional foodstuffs and species are less available due to climate change. For many Indigenous peoples, the act of sharing is fundamental to these intra- and intergenerational relationships, sustains cultural practices and shared identity, and underpins subsistence practices.[44,103] A projected health-related consequence of reduced or lost access to the knowledge, experiences, and relationships built on sharing is increased food insecurity for households reliant on subsistence practices.[61] For example, in Alaska, changes in sea ice coverage and thickness and the timing of ice formation (Ch. 9: Oceans; Ch. 26: Alaska) can lead to decreased access to hunting and fishing areas, which can mean people are unable to access food sources (that is, loss of cultural use.[81] This can then result in lost opportunity for the social components of these activities, including reduced community connection (e.g., Donatuto et al. 2014[81]),less food and knowledge sharing, and diminished relationship building.[44,61]

Communities that rely on the natural environment for sustenance and livelihoods are at increased risk for adverse mental health outcomes related to climate change.[104] Many Indigenous communities share a focus on relationships between people and wildlife and on a respect for natural resources.[29,81,105] Climate impacts to lands, waters, foods, and other plant and animal species undermine these relationships, affect place-based cultural heritages and identities, and may worsen the historical trauma still experienced by many Indigenous peoples.[86,101,102] For example, in

Arctic Indigenous communities, changing wildlife and vegetation patterns are disrupting traditional and subsistence practices and have been associated with increased rates of mood and anxiety disorders; strong emotional responses; and loss of connections to homeland, social networks, and self-worth.[82,101] Additionally, climate impacts that degrade water quality can adversely affect sacred water sources and aquatic species on which subsistence livelihoods and associated relationships are based, increasing the risk of mental health impacts in addition to the well-studied physical health concerns.[53,71] Damage to cultural heritage sites from climate change can affect mental health through impacts to cultural, economic, and social relationships.[106] Media imagery and reports or stories of climate risks and vulnerability also lead to psychological trauma or increased anger, anxiety, depression, fear, and stress.[107] These impacts can intensify existing social stressors, such as loss of jobs and social connections, loss of social support, and family distress.[101,104]

Climate change adaptation measures can reduce physiological vulnerability to health risks; to date, most observational evidence comes from behavioral and public health responses to extreme heat.[108,109,110,111] Organizations including the National Indian Health Board and the Alaska Native Tribal Health Consortium have ongoing efforts to increase Indigenous adaptive capacity specifically for health. Some tribes have climate vulnerability assessments that acknowledge the role of traditional subsistence species, or First Foods, as an essential aspect of health and tribal resilience; for example, the Yurok Tribe assesses the role of salmon in community health,[112] and the Confederated Tribes of the Umatilla Indian Reservation[60] discuss climate risks to salmon, elk, deer, roots, and huckleberry habitat (Ch. 24: Northwest, KM 2). In the Republic of the Marshall Islands, a community-led planning process known as Reimaanlok incorporates traditional knowledge and facilitates local self-determination to support shared goals of climate adaptation, natural resource management, and community health.[85]

Key Message 3

Adaptation, Disaster Management, Displacement, and Community-Led Relocations

Many Indigenous peoples have been proactively identifying and addressing climate impacts; however, institutional barriers exist in the United States that severely limit their adaptive capacities. These barriers include limited access to traditional territory and resources and the limitations of existing policies, programs, and funding mechanisms in accounting for the unique conditions of Indigenous communities. Successful adaptation in Indigenous contexts relies on use of Indigenous knowledge, resilient and robust social systems and protocols, a commitment to principles of self-determination, and proactive efforts on the part of federal, state, and local governments to alleviate institutional barriers.

Indigenous peoples have a long and rich history of adaptation to climate variability[1,71,113,114] that is rooted in their dynamic relationships to the natural environment.[115] However, the ability of Indigenous peoples to anticipate and respond to climate change is affected by economic, social, political, and legal considerations that severely constrain their abilities to consider and respond to rapid ecological shifts. Despite the many examples of Indigenous peoples undertaking climate vulnerability assessments and adaptation planning (see Figure 15.1 for

links to information on current adaptation efforts), as the pace of ecological changes increases with climate change, and sociopolitical obstacles to implementing responses continue to exist, there are challenges and barriers to adaptation.[116,117]

Incorporating Indigenous Knowledges in Adaptation

Indigenous knowledge systems can play a role in advancing understanding of climate change and in developing more comprehensive climate adaptation strategies,[6,7,118] in part because they focus on understanding relationships of interdependency and involve multigenerational knowledge of ecosystem phenology (the study of cyclic and seasonal natural phenomena)[6,119,120] and ecological shifts.[25,121] For example, Inupiat residents in Alaska have identified cyclical patterns of coastal erosion, and their understanding of how quickly and in which direction wind and wave energy reaches the coast can help communities prone to flooding.[122] Indigenous adaptation planning, including considerations of issues such as flooding and water rights, benefits from a greater focus on participatory planning in natural resource management.[19,22,123,124,125,126] This planning incorporates local knowledge and values from conception through implementation[127,128,129] in ways that ensure the protection of Indigenous knowledges and Indigenous peoples' rights not to share sensitive information.[22] In this way, traditional ways of knowing are contributing to sustainable land management practices under changing environmental conditions.[130,131,132,133] For example, the Wabanaki Nations of Maine work closely with local researchers, foresters, and landowners as part of the Cooperative Emerald Ash Borer Project to precisely catalogue and map the decline of the native black ash deciduous trees on which these communities rely for economic, cultural, and spiritual practices. The cooperative leverages Indigenous knowledge of environmental history as it relates to the invasive emerald ash borer beetle.[131] Additionally, the Nez Perce Tribe employs Indigenous knowledges as part of an initiative to enhance local salmon populations that have been in decline (Ch. 24: Northwest, KM 2). For more on Indigenous knowledges, see the regional chapters in this assessment.

Limited Access to Traditional Territory and Decision-Making

Historically in North America, Indigenous peoples occupied vast amounts of land and had access to a wide range of natural resources. Under these conditions, high mobility provided a robust response to changing environmental conditions,[122] but such options today are limited or nonexistent. Multiple considerations, such as whether tribes have corporate status, federal recognition, reservation lands, off-reservation resource rights, specified water rights, access to Ceded Territories and traditional resources, among many others, affect how Indigenous communities develop and implement climate adaptation efforts.[22] Specifically, limitations on the abilities of tribal individuals, communities, businesses, and governing bodies to manage land, participate in policymaking, and access various resources can act as barriers to climate adaptation efforts. Federally recognized tribes have access to a distinct array of resources, programs, and legal authorities, yet they still face numerous limitations in their abilities to implement adaptive strategies. For example, when ecosystems or species' habitats or migration routes shift due to changes in climate, tribes' rights to gather, hunt, trap, and fish within recognized areas are constrained by reservation or other legally defined borders, making adaptation more challenging.[22,40,48,134] This is also the case when federal or state regulations fail to prioritize Indigenous peoples' access to traditional resources. Tribes with noncontiguous reservation lands can be negatively impacted by non-tribal landowners who do not support

climate adaptation efforts, and many Indigenous peoples lacking federal recognition often lack the autonomy, funding, and governmental support to address climate change.[31,48,135,136] Because of these and other considerations, decisions regarding natural resource use are often made without appropriate consultation and collaboration with Indigenous peoples,[19] a process that further inhibits local adaptive capacity.

Disaster Management

As in many communities, Indigenous peoples are experiencing climate change impacts from more frequent and severe weather events, including drought, heat waves, hurricanes, torrential downpours, and flooding (Ch. 2: Climate).[137] In recent years, the Federal Government has made amendments to disaster recovery laws that provide more autonomy to tribes in managing disaster recovery, including the Sandy Recovery Improvement Act of 2013, which grants tribes the authority to request a disaster declaration and assistance from the President, instead of relying on state authorities.[138] However, many tribes continue to face hurdles to disaster management and disaster risk reduction planning. A study of tribes' participation in the federally run and subsidized National Flood Insurance Program finds that, as of 2012, only 7% of tribal communities were participating in the program due to lack of information, limited local government capacity, and limited land jurisdiction.[139]

Risk management and feasible adaptation options are also limited by fundamental issues with federal disaster funding that can be especially prohibitive for tribes. Federal programs are designed to offer extensive emergency relief after disasters have occurred, but they have only limited funding for hazard mitigation or preparation for long-term environmental change.[140] Most slow-onset disasters, such as erosion, are absent from the Federal Government's primary disaster recovery legislation, the Stafford Act, making it particularly challenging to prepare for changing coastlines.[141,142] Additionally, the low population and rural contexts of many Indigenous communities limit the score they can receive in state and federal cost–benefit analyses, which also severely limits funding for disaster risk reduction.[140,143,144]

Displacement and Relocation

Many Indigenous peoples are now facing relocation due to climate-related disasters, more frequent coastal and riverine flooding, loss of land due to erosion, permafrost thawing, or compromised livelihoods caused by ecological shifts linked to climate change.[7,122,145,146,147] Throughout the 18th, 19th, and 20th centuries, Indigenous peoples were removed in large numbers from their homelands by settler colonial governments, leading, in many cases, to death, diaspora, and socioeconomic struggles. The historical context of forced relocations of Indigenous peoples emphasizes the need for relocation frameworks that protect self-determination.[120,144,146,148]

In various regions of the United States, communities of Indigenous peoples are considering relocation or actively pursuing relocation as an adaptation strategy, including communities in Alaska, the Southeast, the Pacific Islands, and the Pacific Northwest (Figure 15.3) (Ch. 19: Southeast; Ch. 24: Northwest; Ch. 26: Alaska; Ch. 27: Hawai'i & Pacific Islands). The complex barriers to adapting to these extreme circumstances continue to be the lack of statutes and regulations, legal authority, and governance structures that enable federal, state, and local actors to coordinate funding priorities and regulations.[7] For example, many tribal communities facing slow-onset disasters, as described above, fail to qualify for relocation funds because they have not been declared federal disaster areas. Also, because

Isle de Jean Charles, LA, and Kivalina, AK

Figure 15.3: These photos show aerial views of (left) Isle de Jean Charles, Louisiana, and (right) Kivalina, Alaska. As projections of sea level rise and coastal inundation are realized, many impacted communities are confronting political, ecological, and existential questions about how to adapt. Photo credits: (left) Ronald Stine; (right) ShoreZone (CC BY 3.0).

there is no single, comprehensive federal program to assist tribes with relocation efforts, tribes must rely on project-specific funding streams that are not designed for relocation initiatives and that often have conflicting requirements and priorities.[147] These barriers are even more challenging when tribes lack federal recognition.[146,149] Additionally, there is no clear platform through which communities can connect non-Indigenous scientific information with their own knowledge systems to inform local decision-making processes as to whether adaptation is best achieved through relocation or by protecting in place through capital investments such as flood management infrastructure.[150,151] Finally, even if relocation is agreed on and logistically feasible, the challenges associated with maintaining community and cultural continuity often undermine the objective of the adaptation strategy, and models for mitigating the impacts of relocation on cultural institutions are rare and difficult to replicate.[152]

In the past few years, solutions have emerged to better address the need for community-driven relocations, but even these have proven more complex for tribal communities than originally expected. The state-recognized Isle de Jean Charles Band of Biloxi-Chitimacha-

Community Planning

Figure 15.4: Some tribal communities at risk of displacement from climate change are actively planning whole-community relocation strategies. As part of the resettlement of the tribal community of Isle de Jean Charles, residents are working with the Lowlander Center (a local, nongovernmental organization), the State of Louisiana, and others to finalize a plan that reflects the physical, sociocultural, and economic needs of the community. Photo credit: Louisiana Office of Community Development.

Choctaw of Louisiana, in partnership with the Lowlander Center (Figure 15.4), developed a community resettlement plan that was selected in 2016, in conjunction with the State of Louisiana's application to the National Disaster Resilience Competition, to receive funding from the U.S. Department of Housing and Urban Development. Due to restrictions on the funding included within the legislation and the tribe's lack of federal recognition, the state is

managing the resettlement of the entire island community, which limits tribal authority over relocation plans. This arrangement exemplifies one way in which tribes are limited in deploying adaptation strategies when using funds that are not specifically designed to meet the unique needs of tribal communities (Ch. 19: Southeast). Though promising, this solution, to date, is a pilot program through a one-time competitive funding opportunity, and there is no planned ongoing support for other community-led resettlements. Outside of this pilot program, the most promising funding options for facilitating relocations away from changing coastlines are voluntary buyout programs offered by some local, state, and federal entities, but new research suggests that these are particularly ill-suited to tribes because of their focus on individual households, instead of community-wide relocations.[153] Central organizing institutions, such as the Denali Commission that is assessing relocation challenges for communities in rural Alaska, may help provide structure for joint state, federal, and tribal partnerships for pursuing safe, timely, and culturally appropriate relocation. More research would be required to properly assess whether these and other solutions would facilitate action toward safe and self-determined futures for these communities.

Acknowledgments

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Opening Image Credit
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Traceable Accounts

Process Description

The report authors developed this chapter through technical discussions of relevant evidence and expert deliberation via several meetings, teleconferences, and email exchanges between the spring of 2016 and June 2017. The authors considered inputs and comments submitted by the public in response to the U.S. Global Change Research Program's (USGCRP) Federal Register Notices, as well as public input provided through regional engagement workshops and engagement webinars. The author team also considered comments provided by experts within federal agencies through a formal interagency review process.

Additional efforts to solicit input for the chapter were undertaken in 2016–2017. The Bureau of Indian Affairs (BIA) worked with partners, the College of Menominee Nation, and the Salish Kootenai College to develop and execute an outreach plan for the chapter. This included awarding mini-grants for community meetings in the fall of 2016 and attending and presenting at tribally focused meetings such as the American Indian Higher Education Consortium 2016 Student Conference (March 2016), the Annual National Conference of the Native American Fish and Wildlife Society (May 2016), the National Tribal Forum on Air Quality (May 2016), the workshops of Rising Voices (2016, 2017), the Native Waters on Arid Lands Tribal Summit (November 2017), the BIA Tribal Providers Conference in Alaska (November 2017), and the Tribes & First Nations Summit (December 2017), among others. Additionally, through these tribal partners, the BIA provided 28 travel scholarships to interested tribal partners to attend and comment on the initial draft content of all regional chapters at the USGCRP's regional engagement workshops. Additional avenues to communicate during these formal open-comment periods included multiple webinars, website notices on the BIA Tribal Resilience Program page, and email notices through BIA and partner email lists. In particular, the BIA solicited comments from multiple tribal partners on the completeness of the online interactive version of the map in Figure 15.1. Chapter authors and collaborators also presented at interactive forums with tribal representatives, such as the National Adaptation Forum (2017), and in various webinars to extend awareness of formal requests for comment opportunities through the USGCRP and partners, such as the Pacific Northwest Tribal Climate Change Network. The feedback and reports from these activities were used to ensure that the Key Messages and supporting text included the most prominent topics and themes.

Key Message 1

Indigenous Livelihoods and Economies at Risk

Climate change threatens Indigenous peoples' livelihoods and economies, including agriculture, hunting and gathering, fishing, forestry, energy, recreation, and tourism enterprises (*very high confidence*). Indigenous peoples' economies rely on, but face institutional barriers to, their self-determined management of water, land, other natural resources, and infrastructure (*high confidence*) that will be impacted increasingly by changes in climate (*likely, high confidence*).

Description of evidence base

Multiple studies of Indigenous peoples in the United States provide consistent and high-quality evidence that climate change is both a current and future threat to Indigenous livelihoods and economies. The climate impacts on traditional subsistence economies and hunting and gathering activities have been extensively documented and consistently provide qualitative observational evidence of impacts.[4,5,7,22,23,24,25,26,27,28,29,31,32,44] There is also very robust documentation of observed adverse climate change related impacts to Indigenous commercial sector activities in agriculture, fishing, forestry, and energy,[22,29,33,36,37,39,40,41,42,43,44,45,46,47,48,49,73,154] as well as recreation, tourism, and gaming.[5,50,51,52,53] These sectors form the basis of most Indigenous economies in the United States.

Multiple studies also consistently identify funding constraints as barriers to the economic development of federally and non-federally recognized tribes,[21,22] as well as barriers that limit self-determination stemming from historical and ongoing federal oversight of natural resources on tribal trust lands,[8,11,17,18] including energy resources.[77,78] Multiple qualitative studies provide consistent and high-quality evidence of current vulnerabilities and challenges related to infrastructure and linked systems that support Indigenous economies and livelihoods.[19,22,49,73,74,76] Despite these challenges, there is consistent and high-quality evidence supporting the finding that energy development, particularly renewable energy, that is implemented in accordance with Indigenous values holds promise as a source of revenue, employment, economic self-determination, and climate mitigation and adaptation for Indigenous communities.[22,79,80]

The studies cited above consistently conclude that these impacts on livelihoods and economies will increase under future projections of climate change. However, methods for making these determinations vary, and quantitative or modeling results that are specific to Indigenous peoples in the United States are limited.

Major uncertainties

As with all prospective studies, there is some uncertainty inherent in modeled projections of future changes, including both global climate system models and economic sector models. In addition, none of the cited studies explicitly modeled the effects of climate adaptation actions in the relevant economic sectors and the extent to which such actions may reduce Indigenous vulnerabilities.

The literature currently lacks studies that attempt to quantify and/or monetize climate impacts on Indigenous economies or economic activities. Instead, the studies cited above in the "Description of evidence base" section are qualitative analyses. The chapter references Chapter 29: Mitigation for some quantitative studies about climate impacts to U.S. economic sectors, but these are not specifically about Indigenous economies. Quantitative national studies of climate impacts may have general applicability to Indigenous peoples, but their overall utility in quantifying impacts to Indigenous peoples may be limited, because there is uncertainty regarding the extent to which appropriate extrapolations can be made between Indigenous and non-Indigenous contexts.

Other uncertainties include characterizing future impacts and vulnerabilities in a shifting policy landscape, when vulnerabilities can be either exacerbated or alleviated in part by policy changes, such as the quantification and adjudication of federal reserved water rights and the development

of policies that promote or inhibit the development of adaptation and mitigation strategies (for example, the development of water rights for instream flow purposes).[19]

Description of confidence and likelihood

Given the amount of robust and consistent studies in the literature, the authors have *very high confidence* that Indigenous peoples' subsistence and commercial livelihoods and economies, including agriculture, hunting and gathering, fishing, forestry, recreation, tourism, and energy, face current threats from climate impacts to water, land, and other natural resources, as well as infrastructure and related human systems and services. The authors have *high confidence* in the available evidence indicating that it is *likely* that future climate change will increase impacts to water, land, other natural resources, and infrastructure that support Indigenous people's livelihoods and economies. The authors have *high confidence* that Indigenous peoples' economies depend on, but face institutional barriers to, their self-determined management of water, land, other natural resources, and infrastructure, stemming from funding constraints and the complexities of federal oversight of trust resources.

Key Message 2

Physical, Mental, and Indigenous Values-Based Health at Risk

Indigenous health is based on interconnected social and ecological systems that are being disrupted by a changing climate (*high confidence*). As these changes continue, the health of individuals and communities will be uniquely challenged by climate impacts to lands, waters, foods, and other plant and animal species (*likely, high confidence*). These impacts threaten sites, practices, and relationships with cultural, spiritual, or ceremonial importance that are foundational to Indigenous peoples' cultural heritages, identities, and physical and mental health (*high confidence*).

Description of evidence base

Multiple epidemiological studies provide consistent and high-quality evidence that Indigenous peoples face health disparities according to conventional Western science approaches to assessing health risk; in general, Indigenous peoples have disproportionately higher rates of asthma,[90] cardiovascular disease,[91,92,93,94] Alzheimer's disease or dementia,[95,96] diabetes,[97] and obesity.[93] There is also robust qualitative evidence that various social determinants of health affect Indigenous health disparities, including historical trauma,[88,89] institutional racism, living and working circumstances that increase exposure to health threats, and limited access to healthcare services.[87,89] A recent peer-reviewed scientific assessment of health concluded that these health disparities have direct linkages to increased vulnerability to climate change impacts from changes in the pollen season and allergenicity, air quality, and extreme weather events.[98]

Additionally, a number of qualitative studies consistently find that Indigenous health, adaptive capacity, and health disparities/environmental justice issues typically do not capture many of the key elements of health and resilience that are important to Indigenous populations, which include concepts related to community connection, natural resources security, cultural use, education and knowledge, self-determination, and autonomy.[81,82,83,84,85,86] Available qualitative evidence consistently identifies Indigenous peoples as having a unique and interconnected relationship

with the natural environment and wildlife that is integral to their place-based social, cultural, and spiritual identity; intangible cultural heritage (traditions or living expressions transmitted and inherited through generations); and subsistence practices and livelihoods that foster intra- and intergenerational knowledge sharing and relationships.[29,44,61,81,82,86,87,99,100,101,102,103,105] Climate impacts to lands, waters, foods, and other plant and animal species undermine these relationships, affect place-based cultural heritages and identities (including through damage to cultural heritage sites), may worsen historical trauma still experienced by many Indigenous peoples, and ultimately result in adverse mental health impacts.[86,101,102,106] There is robust documentation of observed adverse climate change related impacts on culture and food security,[44,61,99,103] physical health,[98] and mental health.[71,101,102,104,107]

The studies consistently conclude that these adverse impacts to culture,[61,155] food security,[61,99] and overall human health[98,99,101,102] will continue under future projections of climate change, though methods for making these determinations vary, and there are limited quantitative or modeling results that are specific to Indigenous peoples in the United States.

There is consistent evidence from behavioral and public health research showing that responses to extreme heat serve as examples of climate change adaptation.[108,109,110,111] There are also multiple examples of tribal health vulnerability assessments that acknowledge the role of traditional subsistence species, or First Foods, as an essential aspect of health and tribal resilience.[60,112] One example from the Republic of the Marshall Islands illustrates a community-led planning process that incorporates traditional knowledge, facilitates local self-determination, and supports climate adaptation, natural resource management, and community health goals.[85]

Major uncertainties

The literature currently lacks national-scale studies that quantify and/or monetize climate impacts on Indigenous health, either through traditional Western science health metrics or Indigenous values-based metrics and indicators of health. There are quantitative studies of specific health-relevant topics, such as climate impacts to air quality (Ch. 13: Air Quality) or extreme heat (Ch. 29: Mitigation), but health impact models have not to date been used to model Indigenous population-specific climate impacts. Quantitative national studies of climate impacts may have general applicability to Indigenous peoples, but their overall utility in quantifying impacts to Indigenous peoples may be limited, because there is uncertainty regarding the extent to which appropriate extrapolations can be made between Indigenous and non-Indigenous contexts. In addition, none of the studies explicitly modeled the effects of climate adaptation actions and the extent to which such actions may reduce Indigenous vulnerabilities or projected future impacts.

Other uncertainties include characterizing future impacts and vulnerabilities in a shifting policy landscape, in which vulnerabilities can be either exacerbated or alleviated in part by policy or programmatic changes, such as a recognition of the non-physiological aspects of Indigenous health.

Description of confidence and likelihood

Based on available evidence, the authors have *high confidence* that Indigenous health is based on interconnected social and ecological systems that are being disrupted by a changing climate. The authors have *high confidence* in the available evidence indicating that it is *likely* that future climate

change will increase impacts to lands, waters, foods, and other plant and animal species and that Indigenous health will be uniquely challenged by these impacts. The authors have *high confidence*, based on the quality of available evidence, that the lands, waters, foods, and other natural resources and species are foundational to Indigenous peoples' cultural heritages, identities, and physical and mental health due to their essential role in maintaining Indigenous peoples' sites, practices, and relationships with cultural, spiritual, or ceremonial importance.

Key Message 3

Adaptation, Disaster Management, Displacement, and Community-Led Relocations

Many Indigenous peoples have been proactively identifying and addressing climate impacts; however, institutional barriers exist in the United States that severely limit their adaptive capacities (*very high confidence*). These barriers include limited access to traditional territory and resources and the limitations of existing policies, programs, and funding mechanisms in accounting for the unique conditions of Indigenous communities. Successful adaptation in Indigenous contexts relies on use of Indigenous knowledge, resilient and robust social systems and protocols, a commitment to principles of self-determination, and proactive efforts on the part of federal, state, and local governments to alleviate institutional barriers (*high confidence*).

Description of evidence base

There is robust documentation of ongoing Indigenous adaptation to climate variability and change.[1,71,113,114,116,117] There is also a very strong evidence base with multiple sources, consistent results, and high consensus that Indigenous peoples face obstacles to adaptation, including:

- a limited capacity to implement adaptation strategies,[19,139,150,151]
- limited access to traditional territory and resources,[6,22,31,48,134,135,136,139,146,149] and
- limitations of existing policies, programs, and funding mechanisms.[6,7,31,135,136,139,140,142,143,144,146,147,149,150,151]

There are many studies that provide evidence with medium consensus that effective participatory planning processes for environmental decision-making (such as for sustainable land management or climate adaptation) are guided by Indigenous knowledge and resilient and robust social systems and protocols).[6,7,118,119,120,127,128,129,131,132,133] In addition, some studies draw conclusions regarding the principles of self-determination in adaptation or relocation planning and decision processes.[144,146,148]

Major uncertainties

Adaptation is still in its infancy in most Indigenous (and non-Indigenous) communities in the United States, so there have not been enough projects implemented all the way to completion to be able to observe results and draw conclusions regarding the efficacy of any particular adaptation process or approach. Extrapolations can be made, however, from other relevant and closely related environmental decision-making processes, such as for land or water resource management.

Description of confidence and likelihood

Based on the quality of available evidence, the authors have *very high confidence* that Indigenous peoples are proactively identifying and addressing climate impacts but that many face various obstacles limiting their implementation of adaptation practices. There is *high confidence* that successful adaptation in Indigenous contexts leverages Indigenous knowledge, robust social systems and protocols, and a commitment to Indigenous self-determination.

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16 Climate Effects on U.S. International Interests

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16 Climate Effects on U.S. International Interests

Container ship bringing goods to port

Key Message 1

Economics and Trade

The impacts of climate change, variability, and extreme events outside the United States are affecting and are virtually certain to increasingly affect U.S. trade and economy, including import and export prices and businesses with overseas operations and supply chains.

Key Message 2

International Development and Humanitarian Assistance

The impacts of climate change, variability, and extreme events can slow or reverse social and economic progress in developing countries, thus undermining international aid and investments made by the United States and increasing the need for humanitarian assistance and disaster relief. The United States provides technical and financial support to help developing countries better anticipate and address the impacts of climate change, variability, and extreme events.

Key Message 3

Climate and National Security

Climate change, variability, and extreme events, in conjunction with other factors, can exacerbate conflict, which has implications for U.S. national security. Climate impacts already affect U.S. military infrastructure, and the U.S. military is incorporating climate risks in its planning.

Key Message 4

Transboundary Resources

Shared resources along U.S. land and maritime borders provide direct benefits to Americans and are vulnerable to impacts from a changing climate, variability, and extremes. Multinational frameworks that manage shared resources are increasingly incorporating climate risk in their transboundary decision-making processes.

Executive Summary

U.S. international interests, such as economics and trade, international development and humanitarian assistance, national security, and transboundary resources, are affected by impacts from climate change, variability, and extreme events. Long-term changes in climate could lead to large-scale shifts in the global availability and prices of a wide array of agricultural, energy, and other goods, with corresponding impacts on the U.S. economy. Some U.S.-led businesses are already working to reduce their exposure to risks posed by a changing climate.

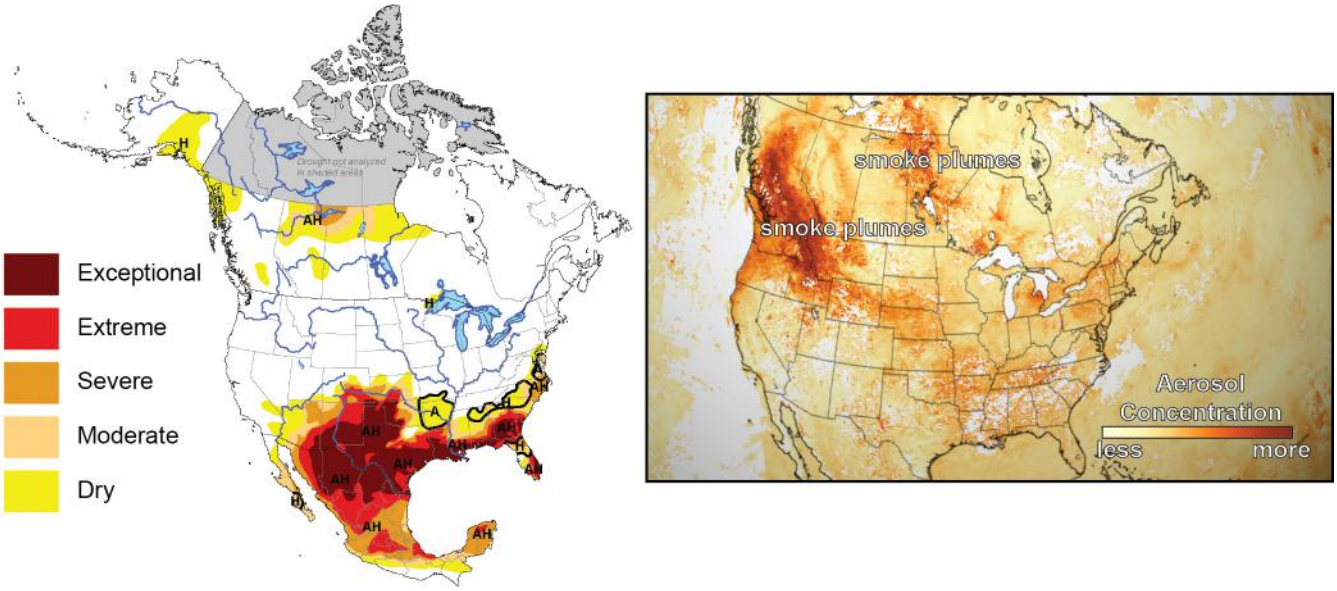
U.S. investments in international development are sensitive to climate-related impacts and will likely be undermined by more frequent and intense extreme events, such as droughts, floods, and tropical cyclones. These events can impede development efforts and result in greater demand for U.S. humanitarian assistance and disaster relief. In response, the U.S. government has funded adaptation programs that seek to reduce vulnerability to climate impacts in critical sectors.

Climate change, variability, and extreme events increase risks to national security through direct impacts on U.S. military infrastructure and, more broadly, through the relationship between climate-related stress on societies and conflict. Direct linkages between climate and conflict are unclear, but climate variability has been shown to affect conflict through intermediate processes, including resource competition, commodity price shocks, and food insecurity. The U.S. military is working to fully understand these threats and to incorporate projected climate changes into long-term planning.

The impacts of changing weather and climate patterns across U.S. international borders affect those living in the United States. The changes pose new challenges for the management of shared and transboundary resources. Many bilateral agreements and public–private partnerships are incorporating climate risk and adaptive management into their near- and long-term strategies.

U.S. cooperation with international and other national scientific organizations improves access to global information and strategic partnerships, which better positions the Nation to observe, understand, assess, and respond to the impacts associated with climate change, variability, and extremes on national interests both within and outside of U.S. borders.

Transboundary Climate-Related Impacts



Shown here are examples of climate-related impacts spanning U.S. national borders. (left) The North American Drought Monitor map for June 2011 shows drought conditions along the U.S.–Mexico border. Darker colors indicate greater intensity of drought (the letters A and H indicate agricultural and hydrological drought, respectively). (right) Smoke from Canadian wildfires in 2017 was detected by satellite sensors built to detect aerosols in the atmosphere. The darker orange areas indicate higher concentrations of smoke and hazy conditions moving south from British Columbia to the United States. *From Figure 16.4 (Sources: [left] adapted from NOAA 2018,[114] [right] adapted from NOAA 2018[115]).*

Introduction

The global impacts of climate (climate change, variability, and extreme events) are already having important implications for societies and ecosystems around the world and are projected to continue to do so into the future.[1,2,3] There are specific U.S. interests that can be affected by climate-related impacts outside of U.S. borders, such as climate variability (for example, El Niño/La Niña events), climate extremes (for example, floods resulting from extreme precipitation), and long-term changes (for example, sea level rise). These interests include economics and trade (Key Message 1), international development and humanitarian assistance (Key Message 2), national security (Key Message 3), and transboundary resources (Key Message 4). While these four topics are addressed separately, they can also affect each other. For example, climate-related disasters in developing countries not only have significant local and regional socioeconomic impacts, but they can also set back U.S. development investments, increase the need for U.S. humanitarian assistance, and affect U.S. trade and national security. U.S. citizens have long been concerned about the welfare of those living beyond U.S. borders and their vulnerability to the global impacts of climate.[4,5]

Key Message 1

Economics and Trade

The impacts of climate change, variability, and extreme events outside the United States are affecting and are virtually certain to increasingly affect U.S. trade and economy, including import and export prices and businesses with overseas operations and supply chains.

The impacts of climate change, variability, and extremes that occur outside the United States can directly affect the U.S. economy and trade through impacts on U.S.-owned, provided, or consumed services, infrastructure, and resources in other countries.[6,7,8,9] Additionally, impacts on foreign-owned infrastructure, services, and resources can have indirect impacts on U.S. trade and businesses that rely on those assets and services, such as impacts on overseas energy and water utilities in places where U.S. international businesses are located. These foreign impacts are in addition to the impacts that climate change, variability, and extreme events within U.S. borders have on the U.S. economy and trade,[10,11] as described elsewhere in the report (for example, Ch. 7: Ecosystems, KM 3).

In addition to local impacts on U.S.-owned assets abroad, climate change is expected to lead to large-scale shifts in the availability and prices of a wide array of agricultural,[12,13] energy,[14,15] and other goods, with corresponding impacts on the U.S. economy. These impacts occur on a wide range of timescales, ranging from months to multiple decades. For example, the prices of agricultural and mining commodities and manufactured goods are affected by year-to-year and decadal climate variations in the availability of irrigation water for agriculture or hydroelectric power.[16,17,18,19] International price changes affect U.S. businesses abroad, as well as U.S. exports and imports. An example is the damaging effect that a series of short-term climate extremes in 2010 and 2011 had on global wheat production. These extremes included drought in Russia, Ukraine, and the United States and damaging precipitation in Australia. A corresponding reduction in wheat production, in combination with high demand, low stocks, trade policies, and other factors, contributed to a spike in global wheat prices.[20] This benefitted U.S. wheat exports while increasing the cost of flour and bread in the United States.[21] This example highlights the complex interactions that often arise through major impacts of overseas climate change, variability, or extremes on U.S. interests (see Key Message 3 for a discussion

of some of the security implications from the 2010–2011 drought).[22] Where these impacts increase global market prices, U.S. purchasers and consumers tend to be harmed, whereas U.S. producers tend to benefit. The opposite is generally true for impacts that drive prices down.

Overseas climate variability, extremes, and change can disrupt U.S. economic interests through impacts to overseas supply chains via impacts to international manufacturing, storage, and transportation infrastructure (road, rail, shipping, and air; Figure 16.1).[23,24,25] At the same time, climate change is creating new transport opportunities, such as the potential summertime availability of trans-Arctic commercial shipping in the next few decades due to a reduction in ice cover caused by warmer temperatures,[26,27,28] though the infrastructure to support this transportation pathway and its safety has not yet been developed (Ch. 26: Alaska, KM 5).

Climate risks are being increasingly recognized and reported by businesses. The Financial Stability Board's Task Force on Climate-related Financial Disclosures (TCFD 2017[29]) has encouraged businesses to report those risks, with hundreds of businesses currently enlisted as partners in the TCFD effort. Some U.S.-led businesses are working to reduce their climate risks abroad. One way they are doing this is through partnerships with environmental groups. For example, Starbucks and Conservation International[30] have partnered to strengthen the capacity of coffee farmers and supply chains to manage climate risks,[31] while Coca-Cola and the World Wildlife Fund are working together to protect foreign watersheds that Coca-Cola uses for water supply.[32] Coca-Cola increased its company-wide water efficiency from 2004 to 2012 by 21.4%, which avoided approximately $600 million in costs and tended to increase resilience in the face of water shortages.[33] As noted in the next section (Key Message 2), U.S. government actions are helping to promote climate resilience of infrastructure services[34,35] and other factors that have the potential to create more stable conditions for American businesses operating in developing countries, as well as promoting the welfare of those countries.

Global trade can promote resilience to climate change by shifting production of goods and services to areas with more favorable climates and away from those with less favorable climates.[36,37,38] However, these shifts will generally have associated costs and may have a harmful effect on communities where production is decreased.

Few studies exist that quantify the impact of climate change on U.S. corporations and the effectiveness of adaptation actions to reduce those impacts.[39]

Impact of 2011 Thailand Flooding on U.S. Business Interests

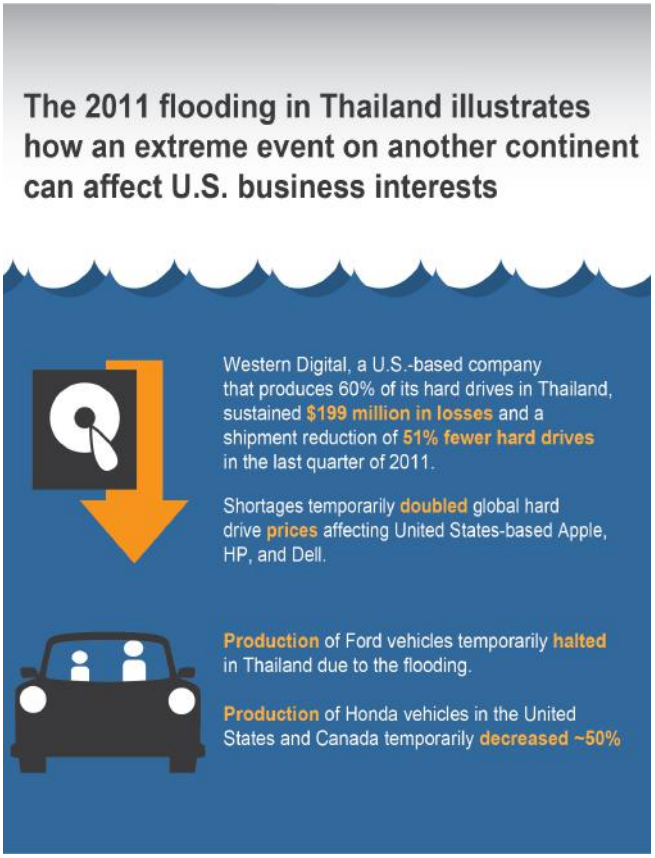


Figure 16.1: Severe flooding in Thailand in 2011 created significant disruptions of local business operations and global supply chains, resulting in a range of impacts to U.S. business interests. Source: ICF.

Key Message 2

International Development and Humanitarian Assistance

The impacts of climate change, variability, and extreme events can slow or reverse social and economic progress in developing countries, thus undermining international aid and investments made by the United States and increasing the need for humanitarian assistance and disaster relief. The United States provides technical and financial support to help developing countries better anticipate and address the impacts of climate change, variability, and extreme events.

U.S. development assistance helps save lives, reduce poverty, and strengthen democratic governance; it also helps societies emerge from humanitarian crises.[40,41] Given their structures and levels of development, the economies and societies of developing countries are generally at greater relative risk from the impacts of climate variability, change, and extremes than are those of developed countries.[1] In addition to causing suffering in developing countries, these impacts threaten to undermine U.S. investments in development and may necessitate additional humanitarian assistance (and possibly military assistance or intervention; see Key Message 3) in response to more frequent and severe natural disasters (such as flooding).

U.S. international development assistance programs, implemented either directly by U.S. government agencies (such as the U.S. Agency for International Development [USAID] and the Millennium Challenge Corporation [MCC]) or indirectly through multilateral institutions (such as the World Bank and United Nations agencies), invest in critical sectors such as agriculture, water and sanitation, health, and infrastructure. These sectors, and the U.S. investments in them, are sensitive to natural variations in climate and extremes and are vulnerable to adverse impacts of climate change.[1,34,42]

The U.S. government systematically identifies climate risks and seeks to reduce the vulnerability of its international development investments. For example, the MCC amended its Environmental Guidelines in June 2012 to formally adopt the International Finance Corporation's Performance Standards on Environmental and Social Sustainability, which includes provisions on climate risk management.[43,44] In addition, USAID has its own climate risk management guidelines.[45] For more than a decade, the U.S. government has also funded adaptation programs that seek to reduce vulnerability to climate impacts in these critical sectors.

Developing countries are often highly vulnerable to climate extremes, which can set back development and increase the need for disaster response and recovery assistance. For example, in 1998, Hurricane Mitch devastated Honduras and Nicaragua, killing thousands of people and causing widespread damage to property and infrastructure.[46] USAID and the U.S. Department of Defense (DoD) jointly responded with an immediate relief effort. USAID also reoriented many of its programs to focus on longer-term recovery.[47] Climate change is likely to increase the demand for U.S. humanitarian assistance of this kind, given the expected increase in the severity of extreme events like tropical cyclones and droughts.[1,48,49]

Many developing countries depend heavily on agriculture as a major source of jobs and a large percentage of their gross domestic product (GDP). Drought can have impacts on food production and security at multiple scales. At the national level, the loss of food and income and the need to help farmers through bad

years can set back development. At the household level, drought can wipe out crops and financial assets and leave families vulnerable to starvation.

The United States works at several levels to help countries anticipate drought and to provide farmers with tools to manage risks to their crops and finances. For example, the United States invests in early warning systems in developing countries such as the Famine Early Warning Systems Network (FEWS NET), a joint effort by multiple U.S. agencies created after a devastating drought in Ethiopia in 1984. Currently, FEWS NET works with governments and international partners in 34 countries (Figure 16.2).[50] In 2015, FEWS NET warned that Ethiopia was facing its worst drought in 60 years and projected that as many as 15 million people would face acute food insecurity. Before the drought and food crisis materialized, USAID mobilized an emergency aid program and provided 680,000 metric tons of food to more than 4 million people.[51]

U.S. investments in making Ethiopian agriculture more climate resilient also helped individual farmers cope with the 2015 drought. A financial risk management program enables farmers to buy "weather index" insurance, which links payouts to certain indicators of extreme weather, such as drought. The insurance program uses information from FEWS NET and coordinates with Ethiopian partners as well as global reinsurance companies. More than 25,000 Ethiopian farmers who purchased this type of insurance received payouts during the drought, helping them to pay off debts, feed their families, and care for livestock.[52,53] Similar index insurance products are being developed through public–private partnerships across Africa, Asia, and Latin America.

Investments by the United States towards enhancing national capacity to produce and use climate information in decision-making, also known as climate services, help countries manage their own risks and build resilience. For instance, the United States collaborated with Jamaica's meteorological service and agriculture ministry to develop a seasonal drought forecast tailored to the needs of Jamaican farmers. Jamaican agriculture was severely affected by drought in 2014.[54] Crop production losses were 57% nationally and close to 75% among farmers identifying climate risks as a major concern. However, farmers who used the drought forecast fully were able to cut their losses nearly in half that year compared to farmers who did not use or did not have access to the forecast.[55]

Climate-resilience investments are being made to assist other key economic sectors in developing countries, including some that are expected to have benefits over longer time frames. For instance, in the Philippines, the United States has supported six cities and provinces to consider climate impacts in the provision of water supply and wastewater treatment services. The project is improving the design, management, and maintenance of long-lived infrastructure, as well as local planning and governance.[56] It assisted one water-scarce city, Zamboanga City, in developing the country's first-ever urban water demand management plan.[57]

Famine Early Warning Systems Network

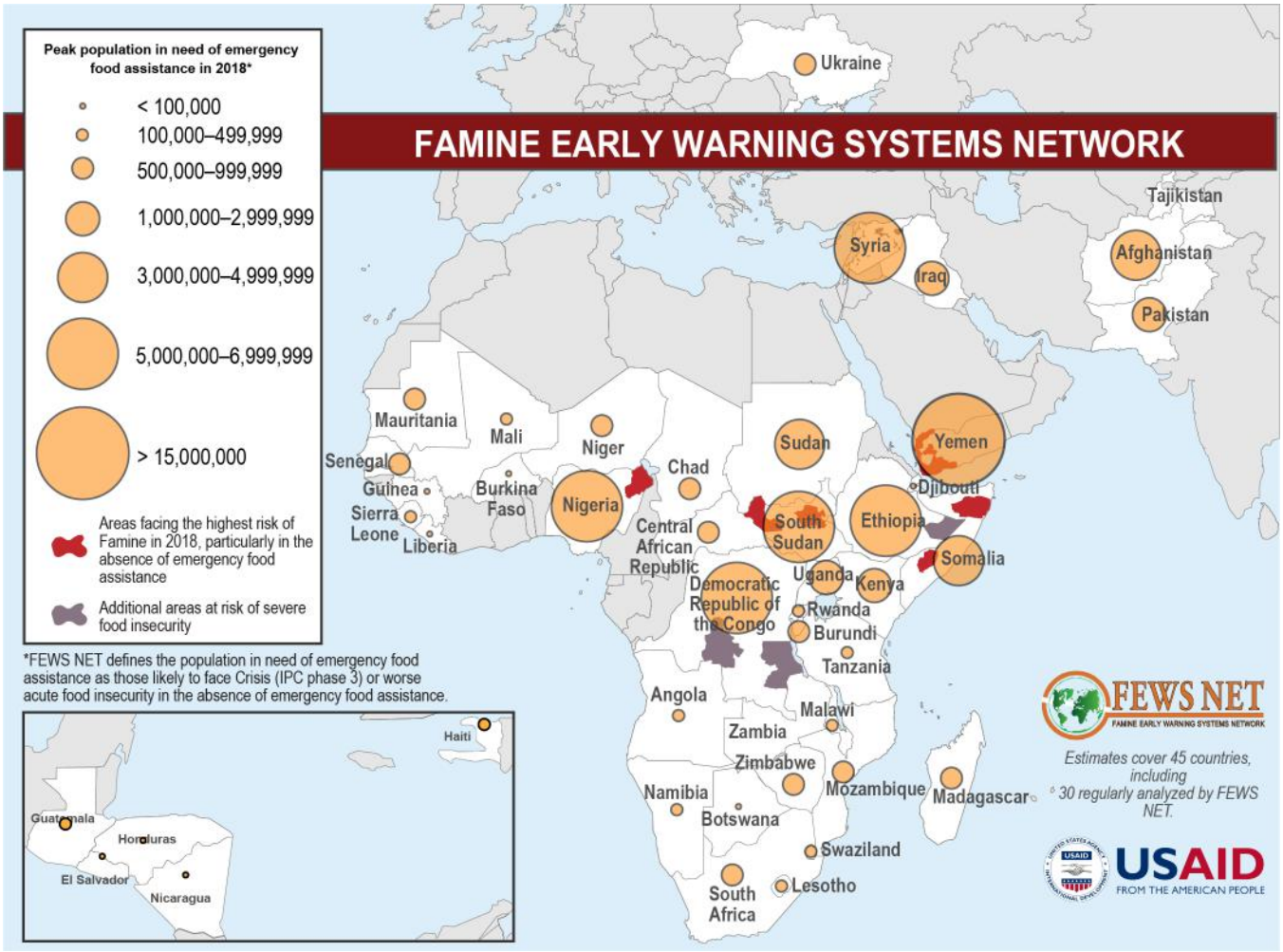


Figure 16.2: The Famine Early Warning Systems Network involves a collaboration between U.S. government agencies, other national government ministries, and international partners to collect data and produce analyses of conditions in food-insecure regions and countries. The analyses integrate information on climate, agricultural production, prices, trade, nutrition, and other societal factors to develop scenarios of food security around the world 6 to 12 months in advance. This map shows projections of peak populations in need of emergency food assistance in 2018. Source: adapted from USAID 2018.[58]

Key Message 3

Climate and National Security

Climate change, variability, and extreme events, in conjunction with other factors, can exacerbate conflict, which has implications for U.S. national security. Climate impacts already affect U.S. military infrastructure, and the U.S. military is incorporating climate risks in its planning.

Climate change and extremes increase risks to national security through direct impacts on U.S. military infrastructure and by affecting factors, including food and water availability, that can exacerbate conflict outside U.S. borders.[59,60] Droughts, floods, storm surges, wildfires, and other extreme events stress nations and people through loss of life, displacement of populations, and impacts on livelihoods.[61,62] Increases in the frequency and severity of such events, as well as other aspects of climate change, may require a larger military mission

focus on climate-sensitive areas such as coasts, drought-prone areas, and the Arctic.[60]

Climate change is already affecting U.S. Department of Defense (DoD) assets by, among other impacts, damaging roads, runways, and waterfront infrastructure.[63] DoD is working to both fully understand these threats and incorporate projected climate changes into long-term planning to reduce risks and minimize impacts. There are many examples of DoD's planning and action for risks to its assets from climate change. DoD has performed a comprehensive scenario-driven examination of climate risks from sea level rise to all of its coastal military sites,[64] including atolls in the Pacific Ocean.[65] In the Arctic, the U.S. Coast Guard and Navy are pursuing strategies to respond to the changing geopolitical significance resulting from the projected absence of summer sea ice in the next few decades (Ch. 2: Climate, KM 7).[66,67,68,69]

The risks climate change may hold for national security more broadly are connected to the relationships between climate-related stresses on societies and conflict. Direct linkages between climate-related stress and conflict are unclear,[70] but climate variability has been shown to affect conflict through intermediate processes, including resource competition, commodity price shocks, and food insecurity.[71,72] The potential for conflict increases where there is a history of civil violence, conflict elsewhere in the region, low GDP or economic growth, economic shocks, weak governance, and lack of access to basic needs.[61] For example, droughts around the world in 2010 contributed to a doubling of global wheat prices in 2011 and a tripling of bread prices in Egypt.[73] This and other factors, including national trade policy and poverty, contributed to the civil unrest that ultimately resulted in the 2011 Egyptian revolution.[73] While the 2010 droughts were not the sole cause of the revolution, they contributed to destabilization of an already unstable region. Likewise, drought in Somalia has forced herders to sell livestock they could not provide for, reducing their incomes and leading some to join armed groups.[74] Water scarcity and climate-related variations in water availability can increase tensions and conflict between countries.[75] In these and other instances, conflict was related to stress from climate-related events, but non-climatic factors also had an important role.[76,77,78,79,80,81,82,83] However, in some cases, water scarcity and variability can result in cooperation rather than conflict.[61,84]

Human migration is another potential national security issue. Extreme weather events can in some cases result in population displacement. For example, in 1999 the United States granted Temporary Protected Status to 57,000 Honduran and 2,550 Nicaraguan nationals in response to Hurricane Mitch.[85] In 2013, more than 4 million people were internally displaced by Typhoon Haiyan in the Philippines,[86] and the United States committed 13,400 military personnel to the relief effort (Figure 16.3).[87] Six months after Typhoon Haiyan, more than 200,000 people remained without adequate shelter.[88] While neither Hurricane Mitch nor Typhoon Haiyan was solely attributable to climate change,[89] tropical cyclones are projected to increase in intensity, which would increase the risk of forced migration.[2,49] Slower changes, including sea level rise and reduced agricultural productivity related to changes in temperature and precipitation patterns, could also affect migration patterns.[61] However, whether migration in response to climate change will generally cause or exacerbate violent conflict is still uncertain (Ch. 27: Hawai'i & Pacific Islands, KM 6).[90,91]

U.S. Military Relief Efforts in Response to Typhoon Haiyan

Figure 16.3: The U.S. military conducted humanitarian and disaster relief efforts in the aftermath of Typhoon Haiyan in the Philippines in 2013. (upper left) An officer aboard an MH-60R Seahawk helicopter prepares to drop off humanitarian supplies. (upper right) A sailor assists a Philippine nurse in treating a patient's head wound at the Immaculate Conception School refugee camp. (lower left) Residents displaced by the storm fill the cargo hold of a C-17 Globemaster aircraft. (lower right) Sailors aboard the aircraft carrier USS *George Washington* move a pallet of drinking water across the flight deck. Photo credit: U.S. Department of Defense.

Key Message 4

Transboundary Resources

Shared resources along U.S. land and maritime borders provide direct benefits to Americans and are vulnerable to impacts from a changing climate, variability, and extremes. Multinational frameworks that manage shared resources are increasingly incorporating climate risk in their transboundary decision-making processes.

The shared borders of the United States are extensive. Land borders with Canada (13 states) and Mexico (4 states) include shared rivers and lakes. Maritime borders are shared with 21 countries by Hawai'i and other island areas, including the U.S. Caribbean, the U.S.-Affiliated Pacific Islands, and the Arctic region.[92,93]

Climate variability and change, as well as related extreme events across shared U.S. borders, can have direct and indirect impacts on those living in the United States. For example, increased temperatures coupled with decreased precipitation in northern Mexico can lead to an increase in the intensity of dust storms and wildfires, which can cross

the border into the United States.[94,95,96,97,98,99] Similarly, transport of smoke from wildfires across the Canadian borders can lead to air quality and health concerns in the United States (Figure 16.4) (see also Ch. 24: Northwest, Box 24.7). Movement of fish species is affected by changes in water temperature (Ch. 9: Oceans, KM 2; Ch. 20: U.S. Caribbean, KM 2) as illustrated by the migration of Pacific hake, an economically important fish species that migrated northward from the United States to Canadian waters due to warmer ocean temperatures during the 2015 El Niño.[100] Additionally, climate impacts are likely to exacerbate cross-border issues related to water, wildlife, trade, transportation, health (Box 16.1) (see also Ch. 14: Human Health), infrastructure, energy, natural resources (such as biodiversity and forests), food security, human migration, and cultural resources. Shared water resources such as rivers and lakes are particularly sensitive to changes in precipitation (Figure 16.4). In the U.S.–Mexico drylands region, large areas are projected to become drier (Ch. 23: S. Great Plains),[101,102] which is expected to present increasing demands for water resources on top of existing stresses associated with population growth.[103,104] Along the U.S.–Canada border, changing weather patterns along the Columbia River, which originates in Canada, affect the amount of water available for irrigation, drinking water supplies, and hydroelectric power generation.[105]

Transboundary Climate-Related Impacts

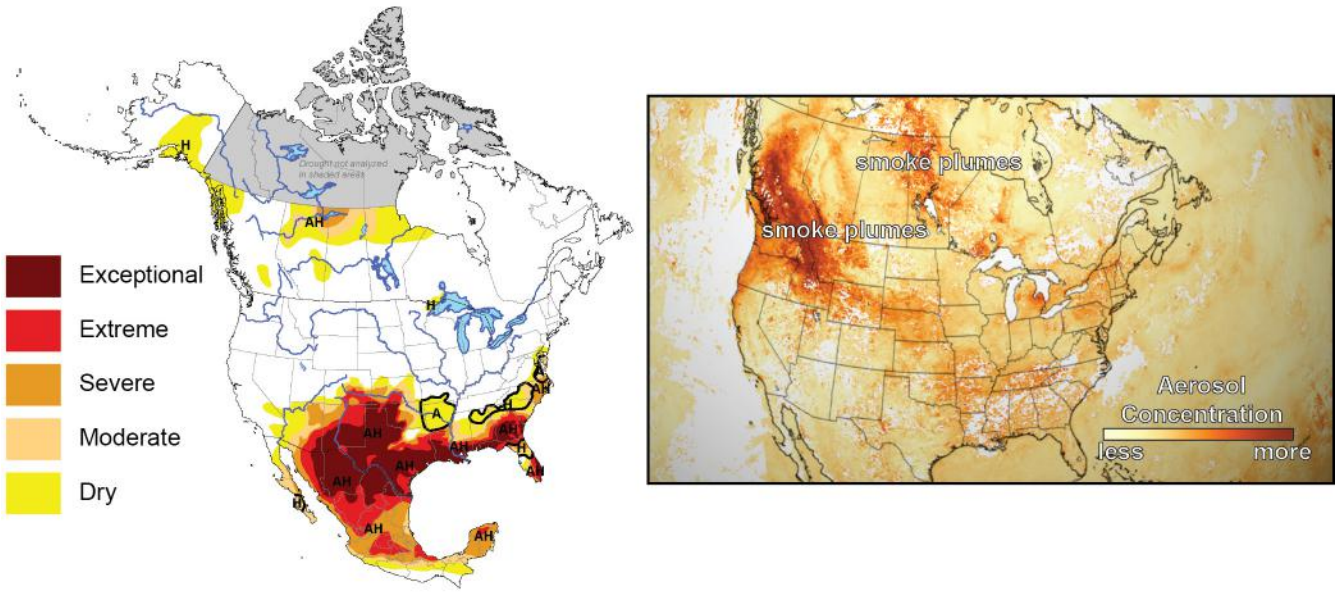


Figure 16.4: Shown here are examples of climate-related impacts spanning U.S. national borders. (left) The North American Drought Monitor map for June 2011 shows drought conditions along the US–Mexico border. Darker colors indicate greater intensity of drought (the letters A and H indicate agricultural and hydrological drought, respectively). (right) Smoke from Canadian wildfires in 2017 was detected by satellite sensors built to detect aerosols in the atmosphere. The darker orange areas indicate higher concentrations of smoke and hazy conditions moving south from British Columbia to the United States. Sources: (left) adapted from NOAA 2018,[114] (right) adapted from NOAA 2018.[115]

Box 16.1: Implications of Global Health Risks for the United States

Climate effects outside the United States can impact human health within the Nation as well as U.S. interests abroad, such as deployed military personnel.[116,117] For example, the past two decades have seen the introduction or reintroduction into the United States of several vector-borne diseases, including West Nile virus, dengue, chikungunya, and, most recently, Zika (Ch. 14: Human Health, Box 14.2).[118,119,120] While climate is only one factor influencing the spread of these diseases, warmer conditions and precipitation changes projected to occur outside and inside the United States could influence disease transmission across and within U.S. borders as well as habitat suitability for disease-carrying insects and pests.[121,122,123] Warmer temperatures provide the opportunity for mosquitoes and other disease-carrying pests to increase their geographic range. These changes, in combination with international travel patterns, could facilitate establishment of these diseases, especially in South Florida, the Texas–Mexico border area, and the U.S. Caribbean Territories.[124,125]

The management process of shared water resources is increasingly incorporating climate information into the decision-making process. Several agreements between countries have recently been restructured to consider changing weather patterns and related management challenges to include climate risk and adaptive management into their near- and long-term strategies. Along the Mexican border, the International Boundary and Water Commission, which implements water treaties between the United States and Mexico, is exploring an array of adaptive water management strategies (Ch. 25: Southwest, Box 25.1)[106] and utilizes an adaptive approach that can help with managing climate-related impacts on Colorado River water.[107] An example of this adaptive management approach is the design of flexible surface water and groundwater storage facilities, coupled with governance mechanisms that continuously account for changing climate conditions and water demand.

The International Joint Commission is also using adaptive management to address climate risks to U.S.–Canadian waters.[108] At the subnational level, the U.S.–Canada Great Lakes Water Quality Agreement incorporated a new annex in 2012 to identify, quantify, understand, and predict the impacts of climate change on Great Lakes water quality,[109] which has helped foster the binational development of new climate products for the Great Lakes (Ch. 21: Midwest, KM 3). Researchers are incorporating climate information into computer models of streamflow and reservoirs along the U.S.–Canada border to help decision-makers understand the long-term potential impacts to flood risk management, hydropower generation, and water availability in the Columbia River Basin.[110] This work is led by U.S. and Canadian agencies in partnerships with academic institutions and regional entities and can be utilized to inform management over long periods of time. These examples of including climate risk into the management of shared river and lake resources can be a model for improving resilience of other shared resources, such as fisheries.

In addition to government-to-government management of transboundary resources, public–private partnerships are increasingly helping to manage climate risks associated with these resources. For example, numerous efforts exist of transboundary collaboration in the Rio Grande–Rio Bravo Basin (Ch. 23: S. Great Plains, Case Study "Rio Grande Valley and Transboundary Issues"), including a bilateral public–private partnership that has implemented collaborative science, restoration, and monitoring actions to restore the river, with climate adaptation as one of the objectives. The partnership consists of businesses, nongovernmental conservation organizations, federal and

state agencies, academic institutions, private foundations, and the public from both Mexico and the United States.[104,111,112,113] The U.S. Caribbean (Ch. 20: U.S. Caribbean, KM 6) and Hawai'i and the Pacific Islands (Ch. 27: Hawai'i & Pacific Islands) are actively engaged with international partners to build adaptive capacity and reduce risks associated with climate change uncertainty at the regional level. Such international engagement may be more in demand in the future to address increasing vulnerabilities of transboundary resources.

Box 16.2: Benefits of International Scientific Cooperation on Climate Research

Cooperation with international science efforts significantly enhances understanding of the impacts of climate variability and climate change here in the United States. As described in the Executive Summary of the recently published *Climate Science Special Report: Fourth National Climate Assessment, Volume I*, changes in the Earth's atmosphere, oceans, land surface, and ice sheets can have major effects on U.S. climate and interests.[3] For example, projected sea level changes in the United States are driven in part by changes that occur outside of our borders in ice sheets, glaciers, and water temperatures.[64,126,127] While localized phenomena, such as coastal subsidence (sinking of land) and regional variance in sea levels, contribute to global sea level rise, understanding the contribution of global-scale changes is critical. Rainfall and temperature patterns in parts of the United States are affected by the El Niño–Southern Oscillation (ENSO), a climatic phenomenon that occurs in the tropical Pacific Ocean. Understanding such global-scale phenomena exceeds the capabilities of any one country alone.[3,128] Furthermore, international collaboration can enhance institutional adaptive capacity as noted in the U.S. Caribbean chapter (Ch. 20) of this report. Through the Global Change Research Act of 1990, Congress recognizes and mandates the importance of U.S. engagement and leadership in international scientific research.[129] Cooperation with other international and national scientific organizations enables the United States to better observe, understand, assess, and manage the impacts of climate processes on U.S. interests within and outside of national borders. Examples of benefits to the United States of international scientific cooperation include

- *access to observations, data, and knowledge* that can shed light on how distant processes affect U.S. climate;[130,131,132]
- *opportunities to leverage funding and equipment* in the development and maintenance of climate observing systems, spreading the cost among countries that participate, including the United States;[133,134,135,136]
- *knowledge of climate impacts in regions and sectors of interest to the United States*, which can be used to inform decisions about humanitarian and development assistance, national security, and transboundary resource management;[51,137]
- *the ability to shape the priorities of an increasingly global and interdisciplinary research community*, which can help focus attention and resources on issues relevant to the United States through participation in joint research efforts[138,139] and assessments;[140,141,142] and
- *mechanisms to share technical expertise and experiences with other countries, regions, and communities with respect to climate services, adaptation, resilience building, and sustainable development* in order to apply lessons learned in other regions to U.S. risk management challenges.[143,144,145,146]

Box 16.3: How Well Are Climate Risks to U.S. International Interests Understood and Addressed?

There is high confidence that climate change, variability, and extreme events can result in profound consequences for U.S. international interests relating to economy and trade (Key Message 1), development and humanitarian assistance (Key Message 2), national security (Key Message 3), and managing shared resources across our borders (Key Message 4). Projections of climate change indicate that these impacts will continue throughout the century and will likely accelerate in the future.[3]

Despite this level of confidence, the mechanisms by which climate impacts beyond American borders can affect U.S. interests are not uniformly well understood. Some of this uncertainty arises because these impacts are part of complex systems, and understanding how climate change, variability, and extremes affect such systems can be challenging (Ch. 17: Complex Systems). For example, as noted in Key Message 3, the connections between climate and national security are complex because national security can be affected through intermediate processes such as resource competition. Such processes are challenging to model and forecast because they can be affected by such difficult-to-predict factors as policy decisions, human behavior, and climate surprises.[147]

In addition, the literature on climate impacts on U.S. international interests is at an early stage of development. For example, while there is a relatively well-developed literature on the potential global economic impacts of climate change (e.g., IPCC 2014, Mani et al. 2018[1,148]), there is a much more limited literature on the implications of such impacts for U.S. businesses, their supply lines, economics, and trade (see Key Message 1). Research on the potential consequences of international climate change on U.S. economics and trade, coupled with analyses of the impacts of climate change within U.S. borders, could provide key insights to better understand impacts and inform actions that promote the well-being of the U.S. economy.

Efforts are underway to adapt to climate change, variability, and extreme events in all four of the Key Message topics addressed in this chapter. However, our understanding about the effectiveness of these particular adaptations and their potential to offset adverse impacts (or take advantage of positive impacts) is quite limited (Ch. 28: Adaptation, Figure 28.1). One explanation is that many of these international-related adaptations have not been in place long (such as the incorporation of climate change projections into transboundary water management efforts; Key Message 4), and there have been relatively few attempts to assess and evaluate their effectiveness. In addition, multiple stakeholders (such as other development organizations, host country governments, nongovernmental organizations, and the private sector) and other factors (such as condition of infrastructure, governance) may have a role in adaptation beyond our borders, thus making it challenging to assess the efficacy of international adaptation actions. Nonetheless, it appears to be highly unlikely that the measures implemented so far will fully avoid or offset the adverse impacts of climate change, variability, and extremes on U.S. international interests.

Acknowledgments

USGCRP Coordinator
Apurva Dave
International Coordinator and Senior Analyst

Opening Image Credit
Container ship: © wissanu01/iStock/Getty Images.

Traceable Accounts

Process Description

The Fourth National Climate Assessment (NCA4) is the first U.S. National Climate Assessment (NCA) to include a chapter that addresses the impacts of climate change beyond the borders of the United States. This chapter was included in NCA4 in response to comments received during public review of the Third National Climate Assessment (NCA3) that proposed that future NCAs include an analysis of international impacts of climate change as they relate to U.S. interests.

This chapter focuses on the implications of international impacts of climate change on U.S. interests. It does not address or summarize all international impacts of climate change; that very broad topic is covered by Working Group II of the Intergovernmental Panel on Climate Change (IPCC; e.g., IPCC 2014[1]). The U.S. government supports and participates in the IPCC process. The more focused topic of how U.S. interests can be affected by climate impacts outside of the United States is not specifically addressed by the IPCC.

The topics in the chapter—economics and trade, international development and humanitarian assistance, national security, and transboundary resources—were selected because they illustrate ways in which U.S. interests can be affected by international climate impacts. These topics cut across the world, so the chapter does not focus on impacts in specific regions.

The transboundary section was added to address climate-related impacts across U.S. borders. While the regional chapters address local and regional transboundary impacts, they do not address impacts that exist in multiple regions or agreements between the United States and its neighbors that create mechanisms for addressing such impacts.

The science section is part of the chapter because of the importance of international scientific cooperation to our understanding of climate science. That topic is not treated as a separate section because it is not a risk-based issue and therefore not an appropriate candidate to have as a Key Message.

The U.S. Global Change Research Program (USGCRP) put out a call for authors for the International chapter both inside and outside the Federal Government. The USGCRP asked for nominations of and by individuals with experience and knowledge on international climate change impacts and implications for the United States as well as experience in assessments such as the NCA.

All of the authors selected for the chapter have extensive experience in international climate change, and several had been authors on past NCAs. Section lead assignments were made based on the expertise of the individuals and, for those authors who are current federal employees, based on the expertise of the agencies. The author team of ten individuals is evenly divided between federal and non-federal personnel.

The coordinating lead author (CLA) and USGCRP organized two public outreach meetings. The first meeting was held at the Wilson Center in Washington, DC, on September 15, 2016, as part of the U.S. Agency for International Development's (USAID) Adaptation Community Meetings and solicited input on the outline of the chapter and asked for volunteers to become chapter authors or otherwise contribute to the chapter. A public review meeting regarding the International

chapter was held on April 6, 2017, at Chemonics in Washington, DC, also as part of USAID's Adaptation Community Meetings series. The USGCRP and chapter authors shared information about the progress to date of the International chapter and sought input from stakeholders to help inform further development of the chapter, as well as to raise general awareness of the process and timeline for NCA4.

The chapter was revised in response to comments from the public and from the National Academy of Sciences. The comments were reviewed and discussed by the entire author team and the review editor, Dr. Diana Liverman of the University of Arizona. Individual authors drafted responses to comments on their sections, while the CLA and the chapter lead (CL) drafted responses to comments that pertained to the entire chapter. All comments were reviewed by the CLA and CL. The review editor reviewed responses to comments and revisions to the chapter to ensure that all comments had been considered by the authors.

Key Message 1

Economics and Trade

The impacts of climate change, variability, and extreme events outside the United States are affecting and are virtually certain to increasingly affect U.S. trade and economy, including import and export prices and businesses with overseas operations and supply chains (*very likely, medium confidence*).

Description of evidence base

Major U.S. firms are concerned about potential climate change impacts to their business (e.g., Peace et al. 2013, Peace and Maher 2015[10,11] and illustrative examples of SEC filings describing climate risks to U.S. companies operating abroad[6,7,8,9]). Examples include the 2011 food price spike[20,21] and the 2011 Bangkok flooding; corresponding prolonged and cascading impacts to transportation and supply chains are documented in the citations related to those issues.[23,24,25] Future changes in precipitation, temperature, and sea level (among other factors) are very likely, as described in USGCRP,[3] and are very likely to exacerbate impacts on the U.S. economy and trade, relative to past impacts.

Major uncertainties

The literature base on the impacts of climate change outside U.S. borders to the U.S. economy and trade is significantly smaller than that on climate change impacts within U.S. borders. In particular, few studies have attempted to quantify the magnitude of the past impacts of climate variability and change that occur outside the United States on U.S. economics and trade. Since there is limited literature, it is unclear how climate-driven regional shifts in economic activity will affect U.S. economics and trade. Nonetheless, the general nature of the main types of impacts described in this section are relatively well known.

Description of confidence and likelihood

The portion of the main message pertaining to the future is *very likely* due to the likelihood of future climate change[3] and persistence of the sensitivity of the U.S. economy and its trade to climate conditions. There is *medium confidence* that climate change and extremes outside the

United States are impacting and will increasingly impact our trade and economy because there is insufficient empirical analysis on the causal relationships between past international climate variations outside the United States and U.S. economics and trade to provide higher confidence at this time. No attempt was made in this chapter to define the net impact of international climate change on the U.S. economy and trade; such a statement would have had very low confidence due to the current paucity of quantitative analyses.

Key Message 2

International Development and Humanitarian Assistance

The impacts of climate change, variability, and extreme events can slow or reverse social and economic progress in developing countries, thus undermining international aid and investments made by the United States and increasing the need for humanitarian assistance and disaster relief (*likely, high confidence*). The United States provides technical and financial support to help developing countries better anticipate and address the impacts of climate change, variability, and extreme events.

Description of evidence base

The link between climate variability, natural disasters, and socioeconomic development is fairly well established (e.g., UNISDR 2015, Hallegatte et al. 2017[149,150]), though some uncertainties about this relationship remain.[151] Humanitarian disasters driven by climate impacts have led to specific changes in U.S. development assistance. For instance, the Famine Early Warning Systems Network (FEWS NET) was created after the droughts that contributed to mass starvation in Ethiopia in the mid-1980s. More recent crises in the Horn of Africa prompted major investments in resilience at the USAID.[152]

The relationship between climate change and socioeconomic development has been assessed extensively by the Intergovernmental Panel on Climate Change through its assessment reports (e.g., IPCC 2014[1]). There is some research on the economic costs and benefits from climate change (e.g., Nordhaus 1994, Stern et al. 2006, Estrada et al. 2017, Tol 2018[153,154,155,156]). However, it can be difficult to separate climate impacts on a sector from the role of other impacts, such as weak governance (Ch. 17: Complex Systems).

The United States has long invested in socioeconomic development in poorer countries with the intention of reducing poverty and encouraging stability. Additionally, stable and prosperous countries make for potential trading partners and a reduced risk of conflict. These ideas are presented in numerous U.S. development, diplomacy, and security strategies (e.g., U.S. Department of State and USAID 2018, 2015[40,41]). There is ample evidence that the United States has invested in measures to reduce climate risks and build resilience in developing countries (e.g., USAID 2016[157]). However, this chapter does not assess the efficacy of these efforts.

Major uncertainties

Climate change adaptation is an emerging field, and most adaptation work is being carried out by governments, local communities, and development practitioners through support from development agencies and multilateral institutions. Evaluations of the effectiveness of adaptation

interventions are generally conducted at the project level for its funder, and results may not be publicized. Some research is emerging on the economic benefits of adaptation interventions (e.g., Hallegatte et al. 2016, Chambwera et al. 2014[158,159]). Over time, it is likely that more activities will be implemented, more evaluations will be conducted, and the evidence base will grow.

Description of confidence and likelihood

There is *high confidence* in the Key Message. There is ample evidence that the impacts of climate variability and change negatively affect the economies and societies of developing countries and set back development efforts. There is also evidence of these impacts leading to additional U.S. interventions, whether through humanitarian or other means, in some places.

Key Message 3

Climate and National Security

Climate change, variability, and extreme events, in conjunction with other factors, can exacerbate conflict, which has implications for U.S. national security (*medium confidence*). Climate impacts already affect U.S. military infrastructure, and the U.S. military is incorporating climate risks in its planning (*high confidence*).

Description of evidence base

Based on an assessment of a wide range of scientific literature on climate and security, multiple national security reports have framed climate change as a stressor on national security.[59,60,62,160,161,162,163] A large body of research has examined how stress due to adverse climatic conditions may affect human and national security in relation to conflict. While a few studies clearly link climatic stress to insecurity conflict,[164,165] more often studies do not find a measurable direct response.[70,77,82,166,167,168,169,170] Instead, the relationship between climate and conflict is often framed as climate stress affecting conflict through intermediate processes, including commodity price shocks and food and water security, which are themselves documented stressors on conflict.[61,71,72] Many studies focus on Africa, but evidence exists throughout the world.[76,77,78,80,81,82,83] Additional complexity arises from evidence of a range of societal responses to resource scarcity such as that brought on by climate change and natural variability.[61]

The U.S. military is observing climate change impacts to its infrastructure and is taking a scenario-driven, risk-based approach to address resultant challenges. Exceedance probability plots of the type used to support engineering siting and design analysis were used but modified to include responses to time-specific tidal phases and historical trends to create an estimate of the "present day" exceedance probability. The hindcast projections kept pace with an Intermediate-Low sea level rise scenario of approximately 5 mm/year (about 0.2 inches/year).[171] The focus for Department of Defense (DoD) infrastructure management, however, is the resultant increased trend for exceedances that would challenge infrastructure functional integrity (such as negative impacts to critical roadways and airfields).[171] In an effort to understand risks to the integrity of coastal facilities more broadly, the DoD uses a scenario-driven risk management approach to support decision-making regarding its coastal installations and facilities. The scenario approaches provide a framework for the inherent uncertainties of future events while providing decision support. Scenarios are not simply predictions about the future but rather plausible futures bounded by

observations and the constraints of physics. Using scenarios, decision-makers can then examine risks through the lens of event impacts, costs of additional analysis, and the results of inaction. In this way, inaction is recognized as an important decision in its own right.[64]

Major uncertainties

The impact and risk of conflict related to climate change is difficult to separate from other drivers of environmental vulnerability, including economic activity, education, health, and food security.[61,70] There is currently a lack of robust theories that fully explain causality and associations between climate change and conflict.

Datasets on climate change, conflict, and security are often limited in length and pose statistical difficulties.[70] However, recent advances in statistical analysis have begun to allow the quantification of indirect effects of multiple variables connecting climatic pressures and violence.[172] These results are preliminary, mostly due to a lack of necessary data and the difficulty of quantifying relevant social variables, such as identity politics or grievances. There is a widespread pattern of examining instances of conflict for drivers, precluding the possibility of finding that climate-related stressors did not result in conflict. There is a need to analyze situations where no conflict occurred despite existing climate risks. Intercomparison of quantitative studies of the link between conflict and adverse climate conditions is complicated because the wide range of climatic and social indicators differ in spatial and temporal coverage, often due to a lack of data availability. Prehistoric and premodern evidence of the impact of climate change on conflict is not necessarily relevant to modern societies,[167] and some of the climate shifts currently being faced are unprecedented over centuries to millennia.[170] Therefore, the possible existence of a relationship is better understood than its particulars and is best expressed in the formulation that climate extremes and change *can* exacerbate conflict.

The ongoing Syrian conflict is often framed in terms of climate change. However, it is not possible to draw conclusions on the role of climate in the outcome of an ongoing conflict. Moreover, the role of climate variability (such as drought), the contribution of climate change to such variability, and the contribution of climate variability to the subsequent conflict is a matter of active debate in the assessed literature.[173,174,175,176]

The documented impacts of climate on national security largely occur through processes associated with natural climate variability, such as drought, El Niño, and tropical storms. While observed and projected increases in extreme weather and climate events have been attributed to climate change, uncertainty remains.[48,177,178,179]

Similarly, additional studies are underway to determine the potential impacts of climate change on DoD resources and mission capabilities. Many of these efforts seek to assess the vulnerability of infrastructure to climate change across a wide variety of ecosystems.[180,181,182]

Description of confidence and likelihood

There is consensus on framing climate as a stressor on other factors contributing to national security. Given the knowledge of factors that increase the risk of civil wars, and evidence that some of these factors are sensitive to climate change, the IPCC found justifiable concern that "climate change or changes in climate variability [could] increase the risk of armed conflict in

certain circumstances."[61] However, the literature examining specific causality does not result in a high confidence conclusion to link climate and conflict, which is reflected in the Key Message *medium confidence* assignment. Multiple schools of thought exist on the mechanisms and degree of linkages, and models are incomplete. Data are improving and evidence continues to emerge, but the inconsistent evidence limits our ability to assign a probability to this Key Message.

Nonetheless, with regard to climate impacts on physical infrastructure, the DoD observes changes in the infrastructure at its installations that are consistent with climate change. In keeping with sound stewardship and prudence, it uses scenario-driven approaches to identify areas of risk while continuing to research and provide resilient responses to the observed changes.

Key Message 4

Transboundary Resources

Shared resources along U.S. land and maritime borders provide direct benefits to Americans and are vulnerable to impacts from a changing climate, variability, and extremes (*very likely, high confidence*). Multinational frameworks that manage shared resources are increasingly incorporating climate risk in their transboundary decision-making processes.

Description of evidence base

In the U.S.–Mexico drylands region, large areas are projected to become drier,[102] which will present increasing demands for water resources on top of existing stresses related to population growth.[103,104] There is *high confidence* that resources critical to livelihoods at borders between the United States and neighboring nations are becoming increasingly vulnerable to impacts of climate change and that the multinational frameworks that manage these resources are increasingly incorporating research-based understanding of the climate risks that these resources face. The literature supporting the Key Message is substantial, increasing in quantity and robustness.[96,97,98,99,100,105] The current impacts are well documented, and the projections of future impacts are aligned with the robust projections of future climate variability.[94,95] The literature also provides examples of bilateral agreements and management frameworks in place to manage these resources. Examples of the impacts include the migration northward into Canadian waters of Pacific hake, a migratory species sensitive to water temperature, during periods of warmer water temperature.[100] One example of a bilateral management framework is the inclusion in 2012 of a climate change impacts annex to the U.S.–Canada Great Lakes Water Quality Agreement to identify, quantify, understand, and predict climate change impacts on the water quality of the Great Lakes.[109]

Major uncertainties

Impacts on shared resources along U.S. international borders are already being experienced. Uncertainties about the impacts are aligned with the uncertainties associated with projections of future climate variability. As elaborated upon in multiple regional chapters of this report (Ch. 18: Northeast; Ch. 20: U.S. Caribbean; Ch. 21: Midwest; Ch. 24: Northwest; Ch. 25: Southwest; Ch. 26: Alaska; Ch. 27: Hawai'i & Pacific Islands), weather patterns in these border regions are projected to continue to change with varying degrees of likelihood and confidence.

Description of confidence and likelihood

There is *high confidence* in the main message. There is sufficient empirical analysis on the relationships between past climate variations along U.S. international borders. The statement about the likelihood that impacts on shared resources will affect the bilateral frameworks established to manage these resources is based on expert understanding of the integration of climate risk into existing and future frameworks.

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17 Sector Interactions, Multiple Stressors, and Complex Systems

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17 Sector Interactions, Multiple Stressors, and Complex Systems

Landslide blocking a road in California

Key Message 1

Interactions Among Sectors

The sectors and systems exposed to climate (for example, energy, water, and agriculture) interact with and depend on one another and other systems less directly exposed to climate (such as the financial sector). In addition, these interacting systems are not only exposed to climate-related stressors such as floods, droughts, and heat waves, they are also subject to a range of non-climate factors, from population movements to economic fluctuations to urban expansion. These interactions can lead to complex behaviors and outcomes that are difficult to predict. It is not possible to fully understand the implications of climate change on the United States without considering the interactions among sectors and their consequences.

Key Message 2

Multisector Risk Assessment

Climate change risk assessment benefits from a multisector perspective, encompassing interactions among sectors and both climate and non-climate stressors. Because such interactions and their consequences can be challenging to identify in advance, effectively assessing multisector risks requires tools and approaches that integrate diverse evidence and that consider a wide range of possible outcomes.

Key Message 3

Management of Interacting Systems

The joint management of interacting systems can enhance the resilience of communities, industries, and ecosystems to climate-related stressors. For example, during drought events, river operations can be managed to balance water demand for drinking water, navigation, and electricity production. Such integrated approaches can help avoid missed opportunities or unanticipated tradeoffs associated with the implementation of management responses to climate-related stressors.

Key Message 4

Advancing Knowledge

Predicting the responses of complex, interdependent systems will depend on developing meaningful models of multiple, diverse systems, including human systems, and methods for characterizing uncertainty.

Executive Summary

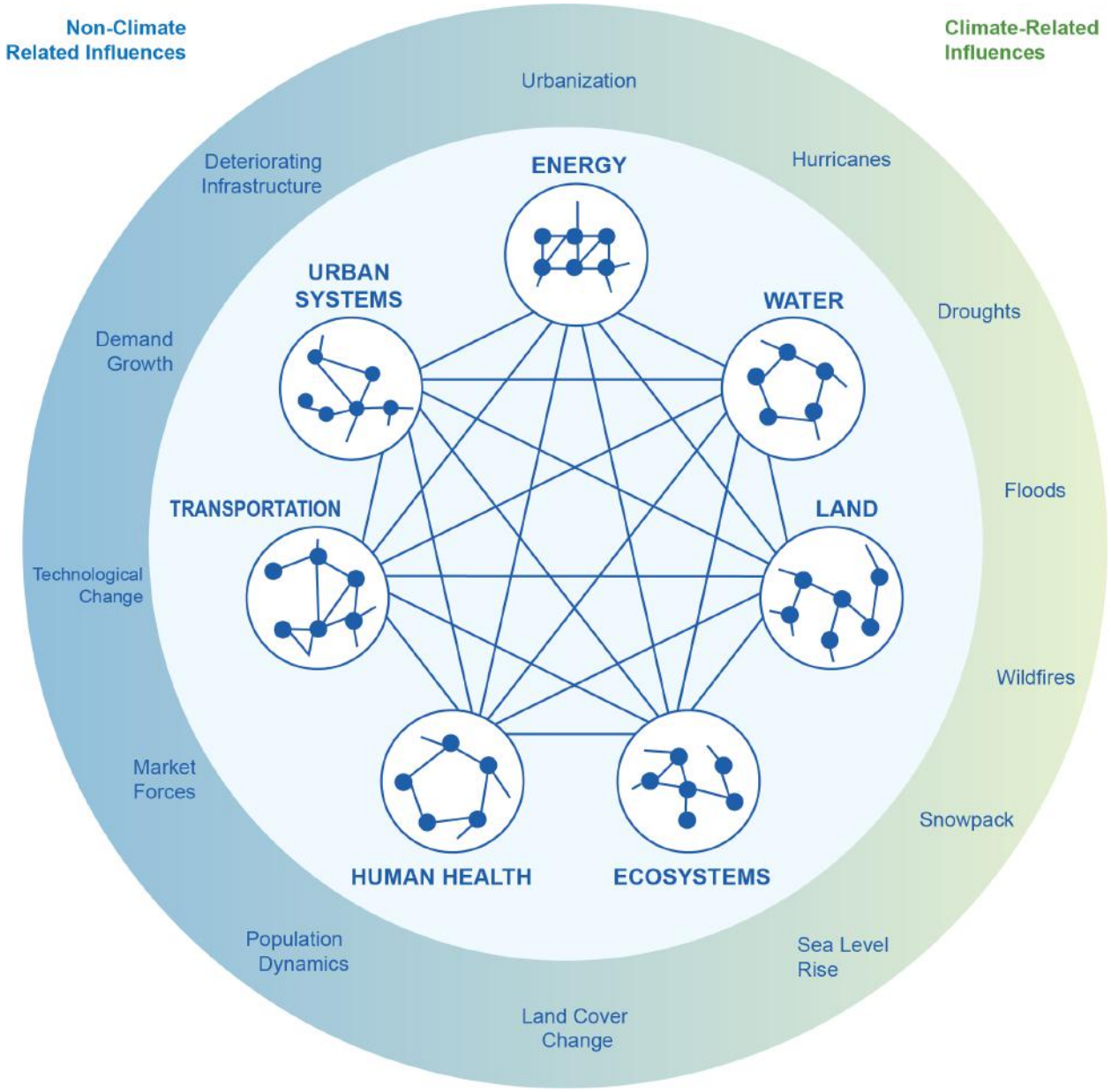
The world we live in is a web of natural, built, and social systems—from global and regional climate; to the electric grid; to water management systems such as dams, rivers, and canals; to managed and unmanaged forests; and to financial and economic systems. Climate affects many of these systems individually, but they also affect one another, and often in ways that are hard to predict. In addition, while climate-related risks such as heat waves, floods, and droughts have an important influence on these interconnected systems, these systems are also subject to a range of other factors, such as population growth, economic forces, technological change, and deteriorating infrastructure.

A key factor in assessing risk in this context is that it is hard to quantify and predict all the ways in which climate-related stressors might lead to severe or widespread consequences for natural, built, and social systems. A multisector perspective can help identify such critical risks ahead of time, but uncertainties will always remain regarding exactly how consequences will materialize in the future. Therefore, effectively assessing multisector risks requires different tools and approaches than would be applied to understand a single sector by itself.

In interacting systems, management responses within one system influence how other systems respond. Failure to anticipate interdependencies can lead to missed opportunities for managing the risks of climate change; it can also lead to management responses that increase risks to other parts of the system. Despite the challenge of managing system interactions, there are opportunities to learn from experience to guide future risk management decisions.

There is a large gap in the multisector and multiscale tools and frameworks that are available to describe how different human systems interact with one another and with the earth system, and how those interactions affect the total system response to the many stressors they are subject to, including climate-related stressors. Characterizing the nature of such interactions and building the capacity to model them are important research challenges.

Complex Sectoral Interactions



Sectors are interacting and interdependent through physical, social, institutional, environmental, and economic linkages. These sectors and the interactions among them are affected by a range of climate-related and non-climate influences. *From Figure 17.1 (Sources: Pacific Northwest National Laboratory, Arizona State University, and Cornell University).*

Introduction

The world we live in is a web of natural, built, and social systems—from global and regional climate; to the electric grid; to water management systems such as dams, rivers, and canals; to managed and unmanaged forests; and to financial and economic systems. Climate affects many of these systems individually, but they also affect one another, and often in ways that are hard to predict. In addition, while climate-related risks such as heat waves, floods, and droughts have an important influence on these interdependent systems, these systems are also subject to a range of other factors, such as population growth, economic forces, technological change, and deteriorating infrastructure (Figure 17.1).

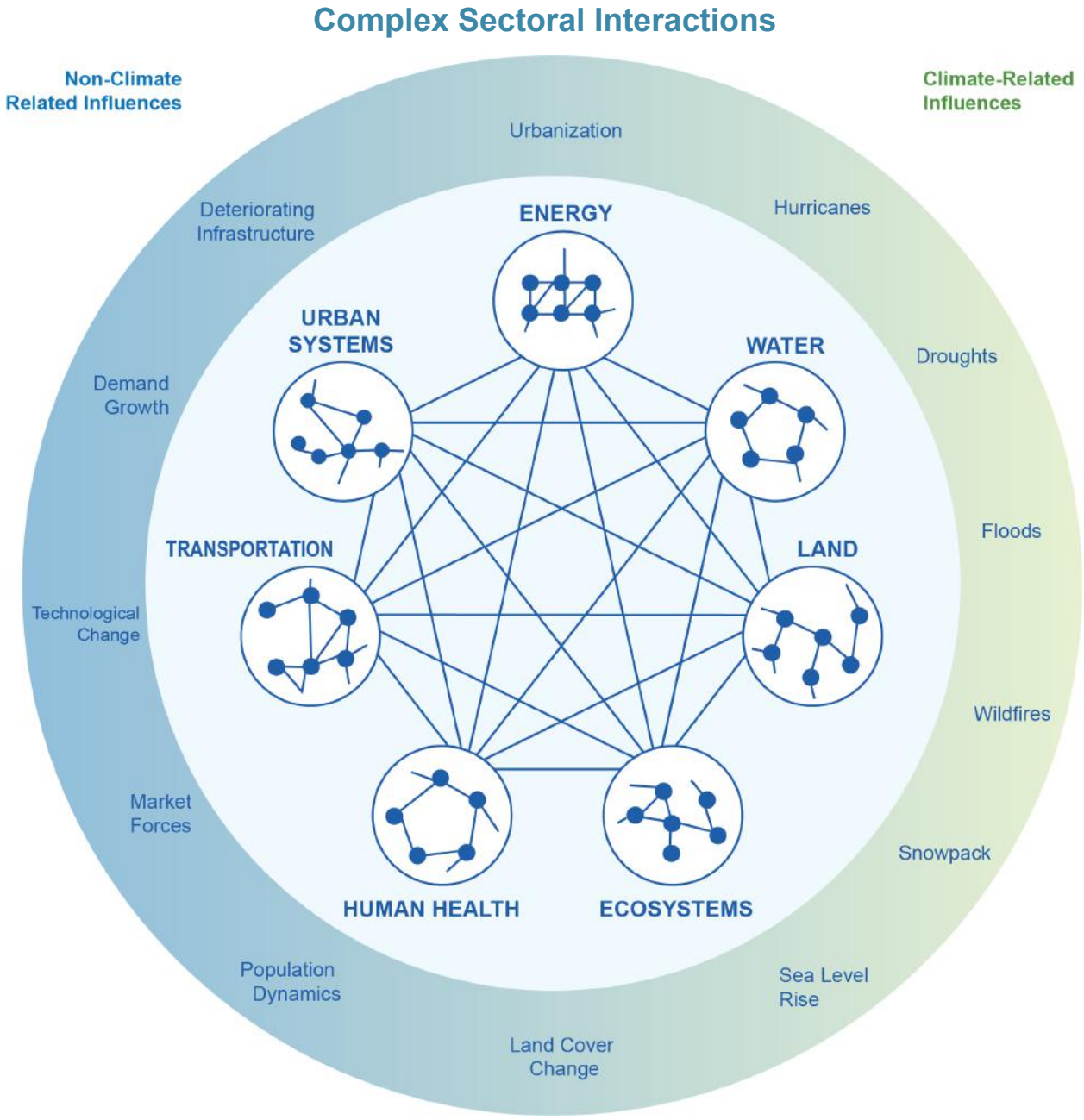


Figure 17.1: Sectors are interacting and interdependent through physical, social, institutional, environmental, and economic linkages. These sectors and the interactions among them are affected by a range of climate-related and non-climate influences. Sources: Pacific Northwest National Laboratory, Arizona State University, and Cornell University.

Assessing the risks associated with climate change requires us to acknowledge that understanding the risks to individual sectors is important but may not always be sufficient to characterize the risks to interdependent systems. Improved understanding of the complex dynamics that arise from interactions among systems is therefore essential to understand risk and manage our response to a changing climate. Characterizing the nature of such interactions and building the capacity to model them are important research challenges.

Regional and Sectoral Summary

Examples of interactions among sectors and systems can be found across the regions in this assessment. The cascading failures resulting from hurricanes are considerations across several coastal regions, including the Southern Great Plains (for example, Hurricane Harvey in 2017; see Box 17.1), the Southeast (for example, Hurricane Irma in 2017), and the Caribbean (for example, Hurricane Maria in 2017). Energy, water, and land systems subject to both climate-related stressors (such as droughts and heat waves) and non-climate influences (such as changes to population, urbanization, and economic development) are important considerations in the Southwest, the Southern Great Plains (for example, the 2012–2015 drought in Texas), and the Northwest (for example, the snow drought in Oregon in 2015). The feedbacks between forest fires and water quality and availability have created challenges in regions including the Southeast (for example, the Appalachian region in 2016) and the Southwest (for example, the Sierra Nevada range over the last five years). Changes in arctic permafrost have caused significant erosion, leading to new risks in transportation and human health in Alaska. The natural gas and other energy industries rely on the effective management of not only railroads and transportation networks but also the diminishing water supply in the Northern Great Plains region. A need for cross-sector planning for climate change impacts in the Great Lakes region has led to new adaptation networks in the Midwest. In Hawai'i, increasing ocean temperatures and ocean acidification threaten coral reefs and marine biodiversity, with attendant economic impacts to tourism, fishery yields, and populations who depend on these for their livelihoods. Increasingly frequent and intense storms, heavy precipitation events, warmer water temperatures, and a rise in sea level in the Chesapeake Bay in the Northeast are projected to impact local populations, who depend on productive fisheries and ecosystems for their livelihoods, resources, and culture.

Box 17.1: Hurricane Harvey: Cascading Failures and Lessons from Emerging Management Approaches

Hurricane Harvey, which struck Houston, Texas, in August 2017 (Figure 17.2), provides a clear example of how impacts from extreme weather events can cascade through tightly connected natural, built, and social systems exposed to severe climate-related stressors (see Key Message 1) (see also Ch. 23: S. Great Plains, Box 23.1 for more information on Hurricane Harvey). Harvey knocked out power to 300,000 customers in Texas,[1] with cascading effects on critical infrastructure facilities such as hospitals, water and wastewater treatment plants, and refineries. Eleven percent of U.S. refining capacity and a quarter of oil production from the U.S. Gulf of Mexico were shut down. Actual and anticipated gasoline shortages caused price spikes regionally and nationally.[2]

In addition to causing direct death and injury, the storm affected public health by disrupting supporting systems. In addition, floodwaters carried toxins and pathogens. Flooding inundated a total of 43 EPA Superfund toxic sites (damaging the protective cap at one site and leading to a short-term release of dioxins), and flooded wastewater treatment plants spilled untreated sewage.[3] Although most hospitals were able to remain open

Box 17.1: Hurricane Harvey: Cascading Failures and Lessons from Emerging Management Approaches, *continued*

(sometimes on backup power), their ability to serve their patients was strained. Widespread power outages forced evacuations that exceeded the emergency shelter capacity, and otherwise healthy people who had no access to shelters or needed power for medical devices turned to hospitals. Roadways clogged with debris, and floodwater hampered the ability to get supplies and evacuate vulnerable patients. Disrupted communications networks interfered with hospitals' ability to coordinate with each other and emergency services.[4]

These interconnected infrastructure systems operate within the context of non-climate influences, including social institutions and policy environments (see Key Message 3) (see also Ch. 11: Urban, Key Message 3). For example, in the area affected by Hurricane Harvey, regional land management practices over the last several decades have reduced the area covered by wetlands, forests, and prairies, which historically absorbed storm water runoff.[5] These natural environments have been increasingly replaced with impermeable surfaces, decreasing Houston's resilience to flooding.[5]

Hurricanes have struck densely populated, interconnected U.S. urban systems several times, including Hurricane Katrina in New Orleans in 2005 and Superstorm Sandy in New York City in 2012. While each city and storm is unique, planners and decision-makers can learn from past events and outstanding examples of resilience. During Harvey, the Texas Medical Center in Houston, the world's largest medical center, remained fully functional despite disruptions to transportation, water, and electricity, in large part due to lessons learned and resilience investments made following the devastation of Tropical Storm Allison in 2001 and Hurricane Ike in 2008.[6] In the aftermath of Superstorm Sandy, the mayor of New York City explicitly brought climate-related risks into response planning and called for a more holistic risk management strategy (see Key Message 3), initiated through the Special Initiative for Rebuilding and Resiliency and the Climate Change Adaptation Task Force.[7] This task force brought together stakeholders from major infrastructure and health sectors such as water, transportation, energy, and communications to recognize and address interdependencies.

Figure 17.2: Hurricane Harvey led to widespread flooding and knocked out power to 300,000 customers in Texas in 2017, with cascading effects on critical infrastructure facilities such as hospitals, water and wastewater treatment plants, and refineries. The photo shows Port Arthur, Texas, on August 31, 2017—six days after Hurricane Harvey made landfall along the Gulf Coast. Photo credit: Staff Sgt. Daniel J. Martinez, U.S. Air National Guard.

Key Message 1

Interactions Among Sectors

The sectors and systems exposed to climate (for example, energy, water, and agriculture) interact with and depend on one another and other systems less directly exposed to climate (such as the financial sector). In addition, these interacting systems are not only exposed to climate-related stressors such as floods, droughts, and heat waves, they are also subject to a range of non-climate factors, from population movements to economic fluctuations to urban expansion. These interactions can lead to complex behaviors and outcomes that are difficult to predict. It is not possible to fully understand the implications of climate change on the United States without considering the interactions among sectors and their consequences.

The sectors and systems subject to climate-related risks do not exist in isolation; they interact with one another and with other sectors and systems. For example, agricultural systems require water for irrigation, which is supplied from lakes, rivers, dams, and reservoirs. Forest management influences the runoff that makes its way into these water systems. Electricity systems use water for hydroelectric power as well as for cooling thermoelectric power plants. Many urban transportation systems rely on electricity to power subways and buses. Meanwhile, medical services, and public health more broadly, are enabled by transportation, water, electricity, and communications (Ch. 11: Urban, KM 3). To most effectively assess the risks associated with climate-related stressors such as floods, droughts, or heat waves, the interactions among these systems must be considered in addition to the effects of these stressors on individual systems.[8]

In addition, climate-related stressors are not the only influences to which natural, built, and social systems are exposed. For example, population movements and demographic changes, economic growth, and changes in industrial activity can all influence systems exposed to climate-related stressors as well as systems that interact with them (see, for example, Box 17.3). Such factors can have powerful impacts on these systems or alter their vulnerability to climate-related stressors. For example, rapid population growth in the coastal United States over the past half-century has significantly increased society's exposure to extreme weather events like hurricanes.[9] These demographic trends may have a greater impact on future hurricane damages than sea level rise or changes in storm intensity.[10]

A long history of research on complex systems (e.g., Simon 2000[11]), spanning disciplines from meteorology[12] to ecology[13] to paleontology[14] to computer science, [15] has shown that systems that depend on one another are subject to new and often complex behaviors that do not emerge when these systems are considered in isolation. These behaviors, in turn, raise the prospect of unanticipated, and potentially catastrophic, risks.[16] For example, failures can cascade from one system to another; that is, failures in one system can lead to increased risks or failures in other systems. Such cascades have been observed with Hurricane Harvey (see Box 17.1), the Northeast blackout (see Box 17.5),[17] and erosion and permafrost thaw in Alaska (Ch. 26: Alaska, KM 3), where failures in physical infrastructure systems had downstream consequences for human health and safety. Tightly connected supply chains can quickly transmit impacts from events such as floods, droughts, heat waves, and tropical cyclones in one region or part of the world to systems in another (see Ch. 16: International, KM 1). For example, the spike in food prices in 2010–2011 was driven in part by drought-related declines in production of basic grains in Australia

and Eastern Europe, which provided a short-term income increase to U.S. farmers of those commodities (see Ch. 16: International, KM 1).[18]

Similarly, changes in one part of a system may alter the thresholds and tipping points in other parts of the system (see Kopp et al. 2017[19]). For example, the overuse and depletion of groundwater removes a backstop in times of drought (see Box 17.3). Forest wildfires can affect water and air quality and render soil impermeable, altering both health and flood risks (see Box 17.4). Interactions among systems can also buffer systems from shocks and introduce a measure of system stability or recovery potential that might not have otherwise existed (see Box 17.5). For example, social networks, which are increasingly reflected in social media enabled by communications infrastructure, can have an important influence on the resilience of communities to natural hazards. Compound events, such as simultaneous temperature extremes and drought, can produce greater economic costs than events considered separately.[19] The complexity of the interactions that exist among these various systems limits the ability to predict the consequences of climate-related stressors with confidence. This poses important challenges for risk assessment as well as the management of those risks.

Box 17.2: Uncovering System Complexities: Wolves and the Yellowstone Ecosystem

A lone gray wolf in Yellowstone National Park. © Michelle Callahan/Flickr (CC BY 2.0).

One challenge in understanding interconnected systems is that interactions are often not revealed until some stress or intervention occurs (see Key Message 1). In addition, societal values and actions can play an important role in such systems. A non-climate example illustrates this challenge very clearly—the consequences of the 1995 reintroduction of wolves into the Yellowstone National Park ecosystem.[20] Concurrent with the eradication of wolves in the early 20th century, streamside willow populations declined as elk herds grew and browsed them more heavily. Willows along the small stream network were reduced to short stature or eliminated entirely. Beavers abandoned streams that lacked willows needed for food and dam construction. In spite of the controversy over wolf reintroductions because of predation on livestock, the National Park Service reintroduced wolves in 1995–1996.[21] Since wolves have been reintroduced, there have been some effects on willow stands, but these appear to largely be due to reductions in overall elk number, rather than strictly to behavioral responses to the presence of the wolves.[22] But in areas where beavers were also lost, the overall system has not returned to its state before the eradication of wolves. The changes due to the loss of beavers have apparently reduced the capacity of the system to return to its original state, even when the wolves returned.[23,24] This example illustrates the unpredictable nature of complex, interconnected systems and how they may react to multiple stressors and interventions driven by societal decisions. It also illustrates that there is no guarantee that such systems, once perturbed, will return to their original state when management actions are taken.[25] Because climate change is a stress that is outside the recent experience of species in many ecosystems, it, too, may uncover complexities due to ecosystem-level interactions that might not be immediately apparent.

Box 17.3: Energy, Water, and Land Linkages

Climate-related stressors such as extreme temperatures, large precipitation events, floods, and droughts highlight the interactions among energy, water, and land systems. These climate-related stressors also interact with non-climate influences such as population, markets, technology, and infrastructure to affect energy, water, and land systems individually as well as the dynamics between these sectors. Understanding how risks evolve under a changing climate, and classifying which risks are the most consequential, poses a significant challenge but is critically important to develop response strategies that enhance resilience across systems. Risks to energy, water, and land systems must be considered in the context of both climate-related and non-climate-related influences as well as the broader social and institutional context (Figure 17.3). As risks evolve, the vulnerabilities and exposure rates for energy, water, and land systems also evolve (see Key Message 1).[26]

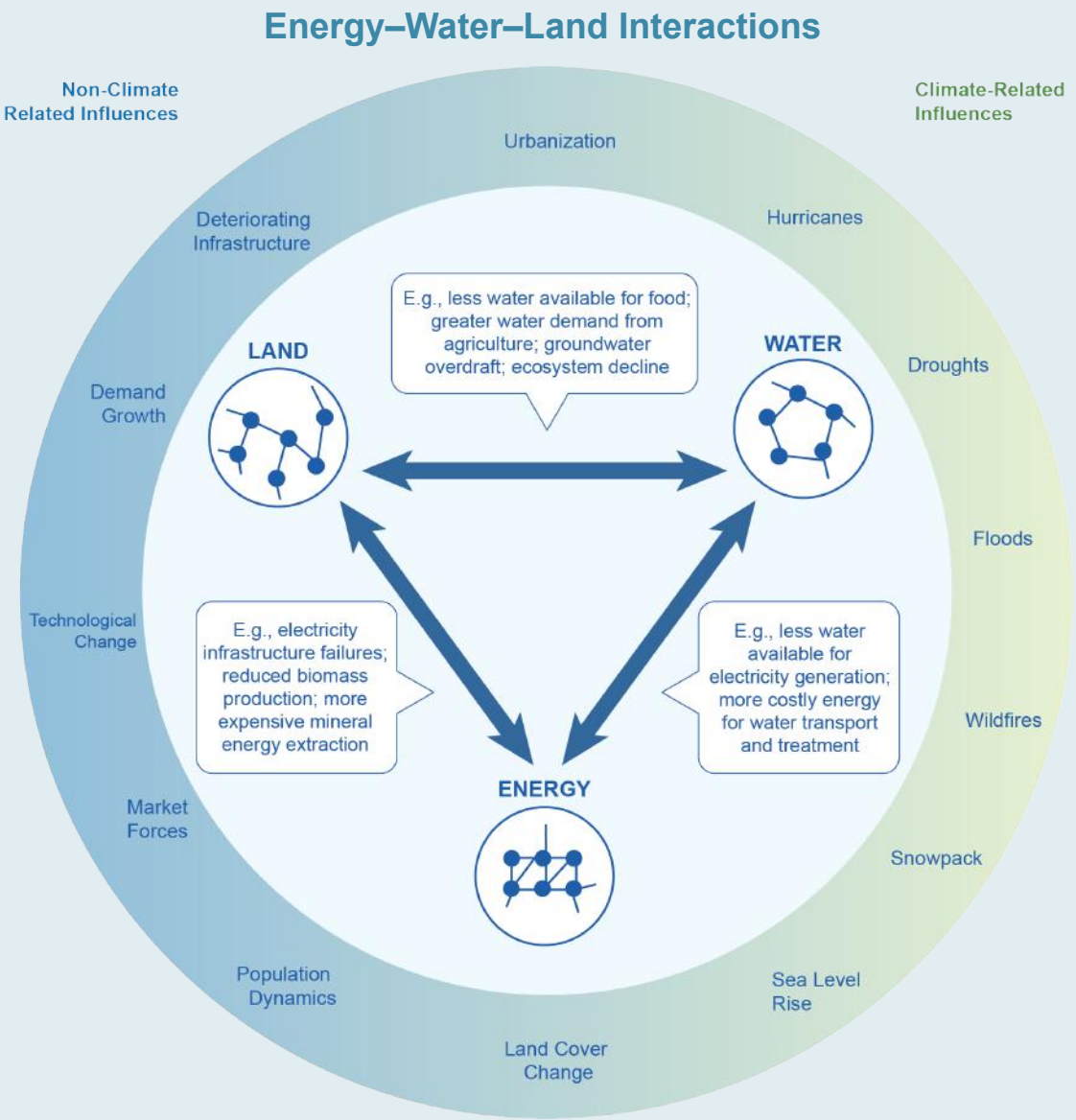


Figure 17.3: Energy, water, and land systems are interconnected and impacted by both climate-related and non-climate stressors. These influences affect these systems individually as well as the dynamics among these sectors. A multisector perspective is necessary to understand risks and develop response strategies that enhance resilience across multiple systems. Sources: Pacific Northwest National Laboratory, Arizona State University, and Cornell University.

Box 17.3: Energy, Water, and Land Linkages, *continued*

The interactions between climate, energy, water, and land in California present a compelling example that illustrates the need to understand complex systems to develop response strategies. Hydropower generation supplies an average of 15% of the state's total electricity consumption,[27] while at the same time the state's thermoelectric power plants rely on water for cooling. Meanwhile, the State Water Project is California's largest single electricity consumer, demanding an average of 2%–3% of total generation for pumping and conveyance.[28] This emphasizes the importance of water for energy and of energy for water.[29] The state's agricultural sector demands approximately 40% of average available freshwater[30] and uses substantial amounts of summer seasonal peak load electricity to pump groundwater, particularly during droughts. Along with uncertainty about future drought and precipitation extremes,[19,31,32] California faces an increasing population, deteriorating infrastructure, and potential energy and water resource limits for an agricultural sector that is evolving to depend on declining groundwater aquifers (Ch. 25: Southwest, KM 1).

The complexity of interconnected energy, water, and land systems highlights the potential impacts of societal choices and the need for institutional integration to explicitly account for sectoral interdependencies and multiple stressors (see Key Message 3).[33,34] Choices in any one sector to confront the many climate-related stressors facing that sector (such as floods, droughts, deteriorating infrastructure, land surface subsidence [sinking], landslides, and wildfires) have the potential to yield cascading cost, reliability, and resilience impacts across the full, connected system (see Key Message 3).[35,36,37,38,39] Taking California's recent droughts as an example, when surface water supplies were strongly curtailed from 2002 to 2016, the result was increased well pumping to meet agricultural demands, which led to a loss of approximately 5.0 cubic miles (20.7 km^3) of groundwater)[40]—or about the size of Lake Powell. Increasing well depths and lost hydropower production influence farmers' decisions about both capital investments in pumping wells and transitions to higher-profit tree and vine crops that cannot be fallowed.[27] Using groundwater as a key economic backstop for agriculture during droughts raises significant concerns about the reversibility of aquifer depletions, the weakening of levees, and accelerating rates of land surface subsidence,[35,39,41,42,43] all of which may alter the future resilience of California's energy, water, and land systems to climate extremes (Ch. 25: Southwest, KM 1).

Key Message 2

Multisector Risk Assessment

Climate change risk assessment benefits from a multisector perspective, encompassing interactions among sectors and both climate and non-climate stressors. Because such interactions and their consequences can be challenging to identify in advance, effectively assessing multisector risks requires tools and approaches that integrate diverse evidence and that consider a wide range of possible outcomes.

The number and complexity of possible interactions among systems affected by climate expand the scope of climate change risk assessment. Recent assessments have acknowledged the importance of this expanded perspective. For example, Chapter 10 of the Third National Climate Assessment (NCA3) [44] highlighted interactions among energy, water, and land systems that people and economies depend on. Other recent climate change impact assessments (e.g., Oppenheimer et al. 2014, Houser et al. 2015, Rosenzweig et al. 2017[45,46,47]) have highlighted risks emerging from interactions among different sectors, geographic regions, and stressors.

A key factor in assessing risk in this context is that it is hard to quantify all the ways in which climate-related stressors might lead to severe or widespread consequences for natural, built, and social systems. A multisector perspective can help identify critical risks ahead of time, but uncertainties will always remain regarding exactly how consequences will materialize in the future. In some cases, interactions are well known. For example, yearly fluctuations in river flows affect hydropower generation, in turn shaping energy costs and profits and reliance on other energy sources (see Box 17.3). Yet even in these cases, it is often difficult to quantify all relevant processes and interactions. Sometimes, interactions are only obvious in retrospect, such as those associated with many past hurricanes (see Box 17.1) or the Northeast blackout (see Box 17.5), with impacts cascading through different parts of the built environment and affecting human health, well-being, and livelihoods. In still other cases, all the relevant interactions are simply not fully understood, for example in the context of the linkages between wildfires, pine bark beetles, and forest management (see Box 17.4).

Therefore, effectively assessing multisector risks requires different tools and approaches than would be applied to understand a single sector by itself. For example, as land management, infrastructure, and climate all change through time, statistical analysis of extreme weather events based on the past becomes less accurate in predicting future outcomes (Ch. 28: Adaptation, KM 2).[48] Approaches can be applied to integrate diverse evidence, combining quantitative and qualitative results and drawing from the natural and social sciences and other forms of analysis.[49,50,51] As one example, models and numerical estimates can be complemented by methods quantifying expert judgment in order to consider uncertainties not well represented by the models. For instance, models and expert judgment have been used together to inform understanding of future sea level rise.[52] Scenarios can also be used to explore preparedness across possible futures, including extreme outcomes that have been rare in historical experience but may be particularly consequential in the future.[50,53,54,55] Such scenarios in assessment can inform understanding of different decisions and choices for managing climate risks, responding to uncertainties about the future by starting with goals and priorities people have.

Box 17.4: Wildfires, Pine Bark Beetles, and Forest Management

Multiple stressors (see Key Message 1) act on U.S. forest ecosystems, impacting wildfire frequency and intensity in complex ways (see Key Message 2) (see also Ch. 6: Forests, KM 1). In the western United States, particularly in Colorado and California, wildfires have become more frequent and larger in area (see Ch. 6: Forests, Figure 6.4; see also Ch. 24: Northwest, KM 1 for an additional example), and this trend is expected to continue as the climate warms (see Ch. 25: Southwest, KM 2).[56] Drought, preceded by warm, wet seasons, can increase fuel flammability and availability. In addition to these climate-related stresses, choices about land use and land-cover change, increased pest populations, human migration, and earth system processes all impact forest ecosystems.[56,57] The interaction of these stressors can alter the vulnerability of these systems, both exacerbating and diminishing the likelihood and impact of wildfire. For example, as humans have moved and expanded the wildland–urban interface, increased fire suppression practices have led to changes in vegetation structure.[58] Without natural fires, vegetation has become denser, resulting in significantly larger and more damaging wildfires.[56] Meanwhile, the interaction of pests with wildfire includes feedback that is oftentimes nonlinear. Warmer winters have allowed pests such as the bark beetle to reach higher elevations and cause significant tree mortality.[59] Insect-killed trees influence fuels and fire behavior, while in some cases wildfire can mitigate the risk of

Box 17.4: Wildfires, Pine Bark Beetles, and Forest Management, *continued*

bark beetle.[58] The impacts of beetle-killed trees on fire likelihood vary over time, with an initial high probability of crown fires followed by the possibility of surface fires.[60]

Wildfires have significant health and economic impacts. Fine particles and ozone precursors released during fires can lead to increased cardiovascular and respiratory damage (Ch. 13: Air Quality, KM 2).[61] Increased wildfires are projected to increase costs associated with health effects, loss of homes and other property, wildfire response, and fuel management.[62] However, risk analysis and planning around wildfire entail the challenge of accounting for all of the stressors acting on the system. Meanwhile, the stressors interact with one another and vary across temporal and sectoral scales (see Key Messages 2 and 4). Efforts are being made to improve prospective vulnerability assessments.[57] The majority of research focuses only on first-order direct fire impacts and fails to recognize indirect and cascading consequences, such as erosion and the health impacts of smoke.[63] To conduct prospective analyses, most modeling efforts include climate and land-use and land-cover change as primary drivers but have a difficult time predicting human-induced stressors such as migration and settlement.[57]

Wildfire at the Wildland–Urban Interface

Figure 17.4: Wildfires pose significant health and economic impacts through interfaces between wildlands and human settlements. Shown here is a wildfire in the Whiskeytown National Recreation Area in California in August 2004. Photo credit: Carol Jandrall, National Park Service.

Key Message 3

Management of Interacting Systems

The joint management of interacting systems can enhance the resilience of communities, industries, and ecosystems to climate-related stressors. For example, during drought events, river operations can be managed to balance water demand for drinking water, navigation, and electricity production. Such integrated approaches can help avoid missed opportunities or unanticipated tradeoffs associated with the implementation of management responses to climate-related stressors.

In interacting systems, management responses within one system influence how other systems respond. Within water basins, for example, upstream management decisions can constrain downstream water-dependent management decisions that affect agriculture, transportation, domestic and commercial use, and environmental protection. Failure to anticipate such interdependencies can lead to missed opportunities for managing the risks of climate change; they can also lead to management responses that increase risks to other parts of the system. For example, the use of groundwater in California as an agricultural backstop in the recent drought may alter California's resilience to future droughts (see Box 17.3).

In practice, managers of agricultural, natural resource, or infrastructure systems do manage at least some degree of system interdependencies. For example, electrical utilities account for the management of water resources to provide power plant cooling capacity, manage fuel supply chains through transportation networks,[64] and manage demand from customers. This requires utilities to acquire appropriate operational permits, licenses, and contracts relevant to other systems and to incorporate the characteristics of those systems in strategic planning and risk management. At the same time, water utilities are users of electricity, particularly those that rely on desalination, which is very energy intensive. Hence, efforts to enhance the resilience of water supply systems to drought can have important consequences for the energy sector and electricity costs.[65] Such indirect risks can be challenging to manage, particularly when system managers have no operational control or jurisdiction over the interacting system. When drought reduced barge traffic on the Mississippi in 2013, farmers had limited options other than seeking more expensive transportation options or incurring delays in getting their products to market.[66,67] More holistic management approaches therefore hold the potential for anticipating these risks and developing effective strategies and practices for risk reduction.

Despite the challenge of managing system interactions, there are opportunities to learn from experience to guide future risk management decisions (Ch. 28: Adaptation, KM 3). The financial sector has invested significantly in understanding and managing systemic risks—including those associated with climate change and climate policy.[68] Mechanisms include risk assessment, financial disclosures, contingency planning, and the development of regulations and industry standards that recognize system interdependencies. Another example is that of the Department of Defense (DoD), which integrates consideration for the implications of climate change and variability for food, water, energy, human migration, supply chains, conflict, and disasters into decision-making and operations around the world.[69] In so doing, the DoD focuses on enhancing preparedness, building partnerships with other public and private organizations, and including climate change in existing planning processes.[69,70]

These strategies are relevant to any organization attempting to enhance its resilience to climate change.

A multisector perspective recognizes that systems have multiple points of vulnerability, that risk can propagate between systems, and that anticipating threats and disruptions requires situational awareness within and between systems.[71,72] Translating the growing awareness of such complexities into the design of policies and practices that effectively address climate change risks, however, requires rethinking how systems are managed in order to identify opportunities for risk reduction or greater efficiency. For example, risk can be reduced by building excess capacity, flexibility, and redundancy into systems.[73] Reserve margins for electricity grids, multi-objective reservoir management, grain storage, multimodal transportation networks, and redundant communications are all mechanisms that provide flexibility for coping with a broad range of risks. Resilience can also be enhanced by planning for system recovery in the event of diverse types of disruptions. For example, restoring power in the wake of a natural disaster is critical for restoring other services such as transportation, water, health, and communications (see Box 17.5). Nevertheless, the costs of designing, constructing, operating, and monitoring resilient, interacting systems that are robust to multiple sources of stress can be significant. Hence, consideration of the costs and benefits of resilience over the entire life cycle of the system may be necessary to make the business case.

Box 17.5: Cascading Failures: Electricity, Public Health, and the 2003 Northeast Blackout

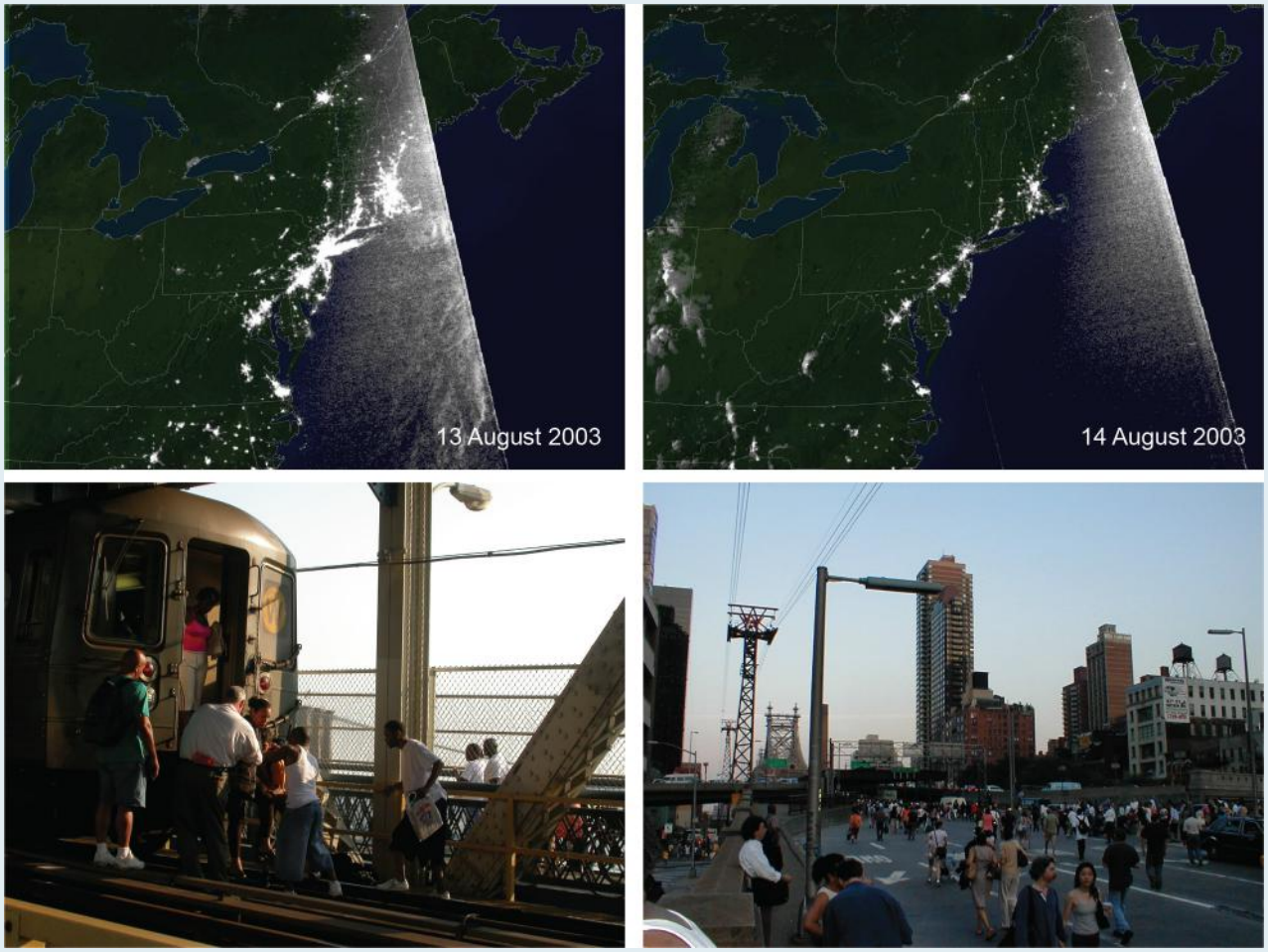
The interactions among severe weather, electric power infrastructure, and public health demonstrate how impacts can cascade within and across sectors (see Key Message 1) and how risk management depends on understanding these interactions (see Key Message 3). The 2016 Climate and Health Assessment identified the impacts of climate-related extreme events on critical infrastructure as a major threat to public health, but it also emphasized the influence of non-climatic factors such as inequalities in income and education as well as individual behavioral choices on health outcomes (Ch. 14: Human Health, KM 1).[67]

More frequent and severe heat waves in many parts of the United States would increase stresses on electric power, increasing the risk of cascading failures within the electric power network that could propagate into other sectors (Ch. 4: Energy, KM 1).[74] Hot weather increases demand for electricity, mostly for residential air conditioning, while reducing transmission efficiency and pushing power infrastructure closer to its operating tolerances (Ch. 4: Energy, KM 1).[75] The Northeast blackout in August 2003, which affected the Northeast and the Canadian province of Ontario, is a familiar example of a cascading network failure that has been well documented (Figure 17.5) (see also Ch. 11: Urban, KM 3). In 2003, a single electrical line warmed on a hot day and sagged into vegetation, tripping out of service. Redirected power overloaded other lines, causing them to trip as well. The disruption cascaded through the network until at the peak of the outage it affected an estimated 50 million people in the Northeast and Canada's Ontario province.[76] Depending on the location, the outage lasted several hours to up to two days, resulting in economic losses of $4–$10 billion due to disruption of businesses and industries.[76]

In the decade following the blackout, despite improvements in reliability and vegetation control standards, weather-related outages actually increased, accounting for 80% of major outages reported; about 20% of weather-related outages cause cascading failures.[77] In addition, today's grid is increasingly large, complex, and heavily loaded, which some researchers suggest increases the potential for blackouts.[78,79] Conversely, others suggest that tighter integration with communications and information technology (IT) infrastructure will improve resilience.[80]

Box 17.5: Cascading Failures: Electricity, Public Health, and the 2003 Northeast Blackout, *continued*

Given the challenges facing today's grid, lessons from the 2003 blackout can still help the public health sector plan for and manage complex consequences of disruptions to interacting infrastructures.[81] Power outages compromise other critical infrastructures, including telecommunications, IT infrastructure, transportation systems, and water and wastewater treatment. In 2003, these disruptions had a broad range of implications for public health, including reduced access to medical equipment and pharmacies, isolation in multistory buildings, slow emergency response times, hospital closures, and temporary loss of disease surveillance systems.[82,83] These impacts translated into health consequences; one study estimated that the event caused 90 excess deaths during August.[83] Maintaining a resilient healthcare infrastructure system therefore depends on being able to successfully adapt, respond, and recover when supporting infrastructure systems are disrupted (see Key Message 3).[84] This reflects the importance of emergency response and disaster risk reduction planning at the community level as well as consideration of the health implications of urban design and infrastructure planning.[67]



Northeast Blackout

Figure 17.5: During the August 2003 blackout, an estimated 50 million people in Canada and the northeastern United States lost power, with cascading impacts on public health and critical infrastructure. These images show (clockwise from upper left): nighttime satellite imagery of the area before the outage; the same view during the blackout; people walking on the Manhattan Bridge; and passengers being evacuated from a subway train on the Manhattan Bridge during the outage. Image credits: (top) NOAA; (bottom left) Jack Szwergold (CC BY-NC 2.0); (bottom right) Eric Skiff (CC BY-SA 2.0).

Key Message 4

Advancing Knowledge

Predicting the responses of complex, interdependent systems will depend on developing meaningful models of multiple, diverse systems, including human systems, and methods for characterizing uncertainty.

Although it is clear that climate-related and non-climate stressors impact multiple natural, built, and social systems simultaneously, thereby altering societal risks, the tools available for predicting these dynamics lag those that predict the dynamics of individual systems. There are many existing modeling efforts that explore complex natural systems, including climate models and numerical weather forecasting models. Although these models are applied to scenarios driven by social and policy decisions, the models themselves rarely incorporate the feedback relationships to social systems and policy contexts.[85,86,87,88] Engineering and resource management models that explicitly incorporate societal economic decisions and represent built systems at a very high resolution have not traditionally been linked to climate projections. Some integrated human–earth system models are explicitly designed to identify system linkages but frequently lack key features or sufficient resolution of the inherent dynamics of the natural environment.[89,90] These and other intersectoral models are also used to create scenarios of how combined natural–human systems might evolve (for example, the Shared Socioeconomic Pathways [SSPs]) (see Scenario Products section of App. 3).[53] Such scenarios can be useful for exploring the range of possible outcomes of larger trends, but the results should not be considered predictive. There is a large gap, therefore, in the multisector and multiscale tools and frameworks that are available to describe how different human systems interact with one another and with the earth system and how those interactions affect the total system response to the many stressors they are subject to, including climate-related stressors.[91] However, increasing recognition of this gap has given rise to a number of innovative research projects that seek to directly link climate scenarios or earth system models to high-resolution models of built infrastructure and human systems (e.g., Allen et al. 2016; Voisin et al. 2016; Ke et al. 2016; Zhou et al. 2017, 2018; Tidwell et al. 2016[92,93,94,95,96,97]).

The responses of interacting systems to both climate-related and non-climate stressors exhibit deep uncertainty, especially when interactions with societal decisions are included. Deep uncertainty arises when there is a lack of clarity about the appropriate models to apply, the relative probability of various scenarios, and the desirability of alternative outcomes.[98] Risk management decisions must therefore be made in the face of these uncertainties (see Key Message 2). An important research challenge is therefore advancing scientific methods and tools that can be applied in climate research, risk assessment, and risk management for complex, interdependent systems under deep uncertainty.[99]

Acknowledgments

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Opening Image Credit
Landslide in California: © gece33/E+/Getty Images.

Traceable Accounts

Process Description

The scope of this chapter was developed to fill a gap in previous National Climate Assessments (NCAs), notably the risks that emerge from interactions among sectors. Previous NCAs have touched on this subject, for example the energy, water, and land use chapter in the Third National Climate Assessment (NCA3). However, these assessments never included a chapter specifically focused on a general treatment of this topic. Emerging scientific research is highlighting the links between sectors and the potential complexity and implications of these interactions, from complex system dynamics such as cascading failures to management approaches and approaches to risk. These concepts were then incorporated into a detailed terms of reference for the chapter, outlining the scope and the general content to be included in the document.

The author team for this chapter was constructed to bring together the necessary diverse experience, expertise, and perspectives. Our authors brought expertise and experience in multiscale, multisector research and modeling, with a focus in specific sectors or sectoral combinations including critical infrastructure, energy–water–land interactions, and ecosystems. The authors also had expertise in complex systems science and previous experience in assessment processes.

The chapter was developed through technical discussions, a literature review, and expert deliberation by chapter authors through email and phone discussions. The team evaluated the state of the science on the analysis of sectoral interdependencies, compounding stressors, and complex system science. Case studies were drawn from a range of sources intended to represent the key themes in the chapter.

Key Message 1

Interactions Among Sectors

The sectors and systems exposed to climate (for example, energy, water, and agriculture) interact with and depend on one another and other systems less directly exposed to climate (such as the financial sector). In addition, these interacting systems are not only exposed to climate-related stressors such as floods, droughts, and heat waves, they are also subject to a range of non-climate factors, from population movements to economic fluctuations to urban expansion. These interactions can lead to complex behaviors and outcomes that are difficult to predict. It is not possible to fully understand the implications of climate change on the United States without considering the interactions among sectors and their consequences. (*High Confidence*)

Description of evidence base

A suite of examples across this assessment and within this chapter demonstrate the interactions between systems and the potentially important implications of these linkages. Examples in this chapter include Hurricane Harvey; the 2003 Northeast blackout; energy–water–land systems in California and throughout the nation; forest systems facing influences from wildfires, drought, and pine bark beetles; and the implications of the reintroduction of wolves in Yellowstone. Each of these examples is supported by its own evidence base; the linkages between systems and the

importance of non-climate influences is self-evident from these examples. Beyond these examples, a small set of recent literature has begun to explore ways to more systematically quantify the implications of including sectoral interdependencies in climate risk assessment (e.g., Harrison et al. 2016[8]).

In addition to literature specific to risk assessment in the context of climate change, there is a long history of research on complex systems[11] that raises the potential for a range of dynamics that might emerge from sectoral interdependencies and compounding stressors. This includes research spanning disciplines from meteorology[12] to ecology[13] to paleontology[14] to computer science.[15] This literature supports the conclusion that more complex dynamics may occur when multiple systems interact with one another.

Major uncertainties

The interactions between sectors and systems relevant to climate risk assessment are self-evident, and there are clear examples of unanticipated dynamics emerging from these interactions in the past. Yet our understanding is limited regarding the precise nature of complex system behavior in the context of climate risk assessment and its ultimate influence on the outcomes of such assessments. As noted in Key Message 4, the available tools and frameworks are simply not sufficient at this point to identify key risks emerging from intersectoral interdependencies and compounding stressors.

Description of confidence and likelihood

We have *high confidence* in this message, because there is high agreement and extensive evidence that a range of critical intersectoral interdependencies and compounding stressors are present and relevant to climate risk assessment. At the same time, the precise impact of these on system dynamics is not well understood.

Key Message 2

Multisector Risk Assessment

Climate change risk assessment benefits from a multisector perspective, encompassing interactions among sectors and both climate and non-climate stressors. Because such interactions and their consequences can be challenging to identify in advance, effectively assessing multisector risks requires tools and approaches that integrate diverse evidence and that consider a wide range of possible outcomes. *(High Confidence)*

Description of evidence base

Recent climate change assessments (e.g., Oppenheimer et al. 2014, Houser et al. 2015[45,46]) emphasize that a multisector perspective expands the scope of relevant risks and uncertainties associated with climate change impacts. Assessing these risks requires attention to multiple interacting sectors, geographic regions, and stressors, such as 1) interactions in the management of water, land, and energy (see Box 17.3), or 2) spatial compounding of impacts if, for example, multiple infrastructure systems fail within a city (see Box 17.1). Risk assessment also requires attention to indirect and long-distance climate change impacts, for instance resulting from human migration or conflict.[45,100] Analyses of historical events (see Box 17.5), evaluations of statistical risk (e.g.,

Carleton and Hsiang 2016[101]), and process-based modeling projections are some of the methods demonstrating these complex interactions across sectors, scales, and stressors.

Different tools and approaches are required to assess multisector risks. Approaches can be applied to integrate diverse evidence, combining quantitative and qualitative results and drawing from the natural and social sciences and other forms of analysis.[47,49,51] For instance, models and expert judgment have been used together to inform our understanding of future sea level rise,[52] and scenarios can also be used to explore preparedness across possible futures.[53,54,55]

Major uncertainties

For interdependent systems affected by multiple stressors, the number and complexity of possible interactions are greater, presenting deeper uncertainties. It is often difficult or impossible to represent all relevant processes and interactions in analyses of risks, especially quantitatively. For example, quantitative projections can evaluate probabilities of well-understood sectoral interactions but will be limited by processes or parameters that are poorly known or unknowable. This is why the integration of diverse evidence and attention to deeper uncertainties are important in multisector risk assessment.

Description of confidence and likelihood

We have *high confidence* in this Key Message because there is high agreement that a multisector perspective alters risk assessment, as is reflected in recent climate change assessments. However, the evidence basis for multisector evaluations is emerging.

Key Message 3

Management of Interacting Systems

The joint management of interacting systems can enhance the resilience of communities, industries, and ecosystems to climate-related stressors. For example, during drought events, river operations can be managed to balance water demand for drinking water, navigation, and electricity production. Such integrated approaches can help avoid missed opportunities or unanticipated tradeoffs associated with the implementation of management responses to climate-related stressors. *(High Confidence)*

Description of evidence base

Recent literature has documented that the management of interacting infrastructure systems is a key factor influencing their resilience to climate and other stressors. A range of studies have argued that the complexity of institutional arrangements in mature, democratic economies like the United States poses challenges to the pursuit of climate adaptation objectives and sustainability more broadly.[72,102,103,104,105] The complexity associated with interacting systems of systems poses significant challenges to integrated management.[105] The allocation of authority and responsibility for system management across multiple levels of government as well as between public and private sectors often contributes to decision-making by one actor being enabled or constrained by other actors.[72,103]

The interdependencies among systems reflect the potential value in the development of more integrated management strategies.[72] This concept of integrated management is reflected in existing literatures, particularly those associated with integrated water resources management [106,107,108,109] and integrated infrastructure planning.[110,111,112] Such studies often address integration within sectors or systems, with less consideration for integration between or among systems. This has the potential to lead to missed opportunities for improving management practice.[72] However, assessments of energy,[113] urban infrastructure,[75] and coupled energy–water–land[114] systems conducted as part of NCA3[44] identified a range of interdependencies across multiple sectors (see Dawson 2015[115]).

A range of strategies have been proposed for enhancing the capacity to manage system interdependencies and climate change risk. Significant effort has been invested in understanding and modeling system dynamics to enhance capabilities for risk and vulnerability assessment. These efforts have largely focused on physical infrastructure systems, infrastructure networks, and the potential for cascading failures.[116,117,118,119] Such capabilities help to identify what can be monitored in complex systems to enhance situational awareness, anticipate disruptions, and increase resilience.[71,120,121]

There is ample evidence of comanagement of interdependent systems, often as a function of resource assurance and/or contingency planning. For example, the use of water for electricity generation (hydropower or cooling in thermal generation) involves regulatory constraints around water use as well as operational decision-making regarding water management.[72,114,122,123,124,125] These interactions have been a major focus of studies addressing the climate–water–energy nexus. Meanwhile, emergency managers as well as agricultural, commercial, and industrial supply chains often develop contingency plans in the event of disruptions of transportation, telecommunications, water, and/or electricity.[81,126,127,128,129]

A key element of such planning is to build redundancy and flexibility into system operations.[73] Evidence suggests that adding flexibility or robustness to systems or transforming systems such that they interact or behave in fundamentally different ways can increase construction, maintenance, or procurement costs.[82,130,131] However, a number of studies exploring the valuation of resilience actions and investments have concluded that the benefits of resilience interventions can be significantly greater than the costs, provided the long-term mitigating effects of the intervention are factored in.[132,133,134]

Given the complexity of governance systems, the responsibility for the design and implementation of such strategies for integrated management rests on a broad range of actors. Over the latter part of the 20th century, the privatization of infrastructure, including energy, telecommunications, and water, transferred infrastructure management, responsibility, and risk to the private sector.[135] Nevertheless, local, state, and federal governments continue to have critical roles in regulation, risk assessment, and research and development. In addition, many institutions, organizations, and individuals either have infrastructure dependencies or influence the dynamics, operations, investment, and performance of infrastructure.[136] The increasing interconnectedness of both infrastructure and the people who use and manage that infrastructure is leading to both new challenges and opportunities for comanaging these systems, particularly in urban areas.[137,138,139]

A growing literature is identifying opportunities to enhance consideration of human health and other benefits in the design of urban landscapes and infrastructure.[67,140,141,142,143]

Major uncertainties

The dominant uncertainties associated with the management of climate risks and system interdependencies include understanding indirect effects and feedbacks between systems, particularly with respect to predicting system responses. Technological change could have significant implications for the resilience, interconnectedness, and responses of systems to climate-related stressors and other disturbances. Such change could increase the complexity of integrated management with implications that could be positive or negative with respect to vulnerability. In addition, the future evolution of governance and regulatory dimensions of infrastructures systems, as well as consumer choices and behavior, are associated with irreducible uncertainty, largely because they involve choices yet to be made.

Description of confidence and likelihood

There is high agreement and extensive evidence that institutional arrangements and governance are critical to the management of systems and their interdependencies. This finding is reflected in scientific assessments, modeling studies, and observations of system responses and performance, as well as in theories emerging from complex systems science. Furthermore, a history of management practice associated with water, energy, transportation, telecommunications, food, and health systems that spans decades to centuries provides evidence for the importance of system interdependencies. Thus, there is *high confidence* in this message.

Key Message 4

Advancing Knowledge

Predicting the responses of complex, interdependent systems will depend on developing meaningful models of multiple, diverse systems, including human systems, and methods for characterizing uncertainty. *(High Confidence)*

Description of evidence base

This Key Message is based on an understanding of a range of analyses and modeling tools described throughout the chapter.

Major uncertainties

Because the Key Message is the authors' assessment of the overall state of development of research tools and models, and the subsequent importance of developing research tools, the concept of major uncertainties is not entirely appropriate. This is a matter of the authors' judgment, not calculation or assessment of underlying probabilities.

Description of confidence and likelihood

See above. No likelihood statement is appropriate, and the *high confidence* is based on the authors' assessment of the underlying literature and development of methods and modeling tools.

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18 Northeast

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18 Northeast

Bartram Bridge in Pennsylvania

Key Message 1

Changing Seasons Affect Rural Ecosystems, Environments, and Economies

The seasonality of the Northeast is central to the region's sense of place and is an important driver of rural economies. Less distinct seasons with milder winter and earlier spring conditions are already altering ecosystems and environments in ways that adversely impact tourism, farming, and forestry. The region's rural industries and livelihoods are at risk from further changes to forests, wildlife, snowpack, and streamflow.

Key Message 2

Changing Coastal and Ocean Habitats, Ecosystems Services, and Livelihoods

The Northeast's coast and ocean support commerce, tourism, and recreation that are important to the region's economy and way of life. Warmer ocean temperatures, sea level rise, and ocean acidification threaten these services. The adaptive capacity of marine ecosystems and coastal communities will influence ecological and socioeconomic outcomes as climate risks increase.

Key Message 3

Maintaining Urban Areas and Communities and Their Interconnectedness

The Northeast's urban centers and their interconnections are regional and national hubs for cultural and economic activity. Major negative impacts on critical infrastructure, urban economies, and nationally significant historic sites are already occurring and will become more common with a changing climate.

Key Message 4

Threats to Human Health

Changing climate threatens the health and well-being of people in the Northeast through more extreme weather, warmer temperatures, degradation of air and water quality, and sea level rise. These environmental changes are expected to lead to health-related impacts and costs, including additional deaths, emergency room visits and hospitalizations, and a lower quality of life. Health impacts are expected to vary by location, age, current health, and other characteristics of individuals and communities.

Key Message 5

Adaptation to Climate Change Is Underway

Communities in the Northeast are proactively planning and implementing actions to reduce risks posed by climate change. Using decision support tools to develop and apply adaptation strategies informs both the value of adopting solutions and the remaining challenges. Experience since the last assessment provides a foundation to advance future adaptation efforts.

Executive Summary

The distinct seasonality of the Northeast's climate supports a diverse natural landscape adapted to the extremes of cold, snowy winters and warm to hot, humid summers. This natural landscape provides the economic and cultural foundation for many rural communities, which are largely supported by a diverse range of agricultural, tourism, and natural resource-dependent industries (see Ch. 10: Ag & Rural, Key Message 4).[1] The recent dominant trend in precipitation throughout the Northeast has been towards increases in rainfall intensity,[2] with increases in intensity exceeding those in other regions of the contiguous United States. Further increases in rainfall intensity are expected,[3] with increases in total precipitation expected during the winter and spring but with little change in the summer.[4] Monthly precipitation in the Northeast is projected to be about 1 inch greater for December through April by end of century (2070–2100) under the higher scenario (RCP8.5).[4]

Ocean and coastal ecosystems are being affected by large changes in a variety of climate-related environmental conditions. These ecosystems support fishing and aquaculture,[5] tourism and recreation, and coastal communities.[6] Observed and projected increases in temperature, acidification, storm frequency and intensity, and sea levels are of particular concern for coastal and ocean ecosystems, as well as local communities and their interconnected social and economic systems. Increasing temperatures and changing seasonality on the Northeast Continental Shelf have affected marine organisms and the ecosystem in various ways. The warming trend experienced in the Northeast Continental Shelf has been associated with many fish and invertebrate species moving northward and to greater depths.[7,8,9,10,11] Because of the diversity of the Northeast's coastal landscape, the impacts

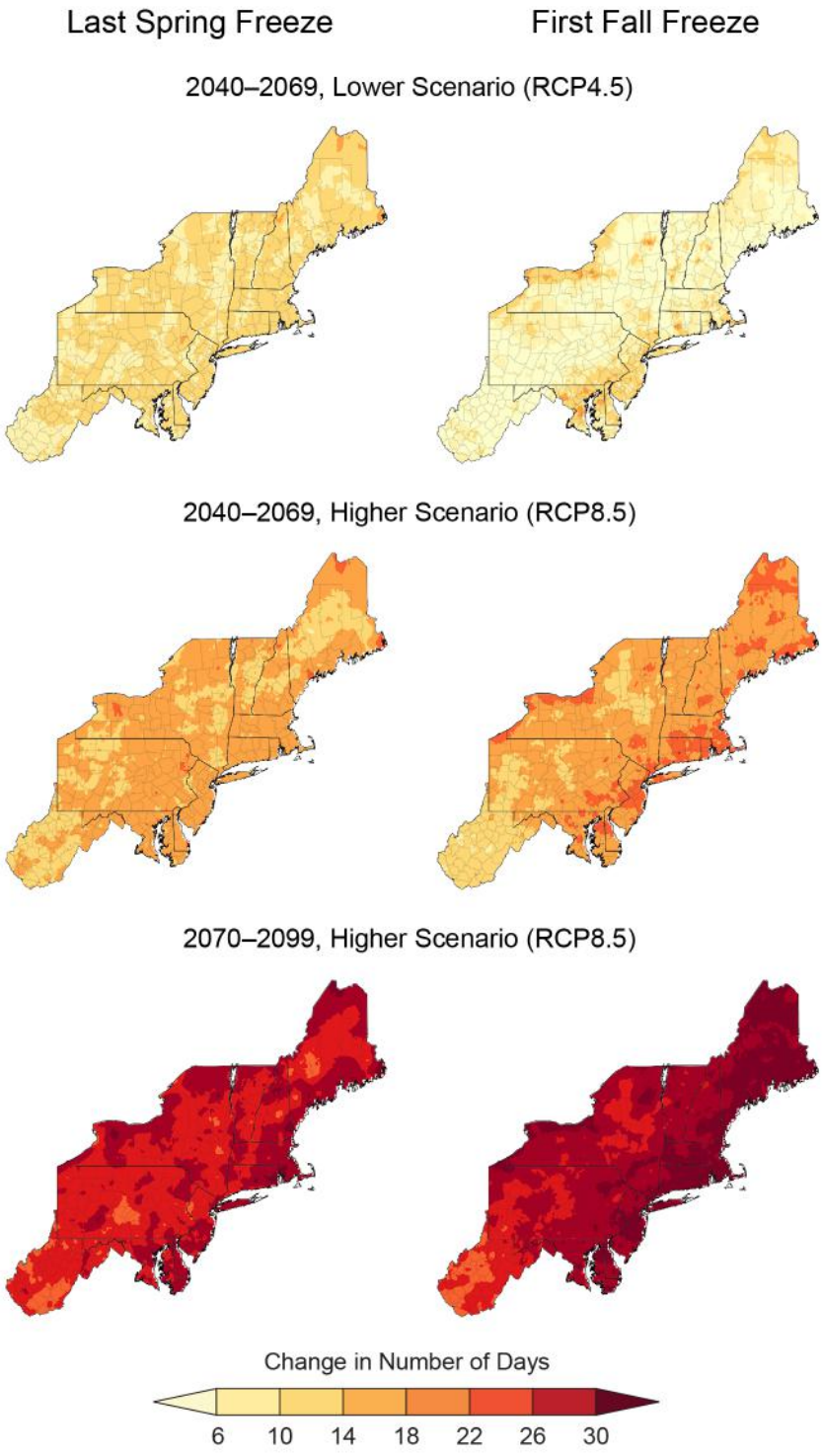
from storms and sea level rise will vary at different locations along the coast.[12,13]

Northeastern cities, with their abundance of concrete and asphalt and relative lack of vegetation, tend to have higher temperatures than surrounding regions due to the urban heat island effect. During extreme heat events, nighttime temperatures in the region's big cities are generally several degrees higher than surrounding regions, leading to higher risk of heat-related death. Urban areas are at risk for large numbers of evacuated and displaced populations and damaged infrastructure due to both extreme precipitation events and recurrent flooding, potentially requiring significant emergency response efforts and consideration of a long-term commitment to rebuilding and adaptation, and/or support for relocation where needed. Much of the infrastructure in the Northeast, including drainage and sewer systems, flood and storm protection assets, transportation systems, and power supply, is nearing the end of its planned life expectancy. Climate-related disruptions will only exacerbate existing issues with aging infrastructure. Sea level rise has amplified storm impacts in the Northeast (Key Message 2), contributing to higher surges that extend farther inland, as demonstrated in New York City in the aftermath of Superstorm Sandy in 2012.[14,15,16] Service and resource supply infrastructure in the Northeast is at increasing risk of disruption, resulting in lower quality of life, economic declines, and increased social inequality.[17] Loss of public services affects the capacity of communities to function as administrative and economic centers and triggers disruptions of interconnected supply chains (Ch. 16: International, Key Message 1).

Increases in annual average temperatures across the Northeast range from less than 1°F (0.6°C) in West Virginia to about 3°F (1.7°C) or more in New England since 1901.[18,19] Although the relative risk of death on very hot days is lower today than it was a few decades ago, heat-related illness and death remain significant public health problems in the Northeast.[20,21,22,23] For example, a study in New York City estimated that in 2013 there were 133 excess deaths due to extreme heat.[24] These projected increases in temperature are expected to lead to substantially more premature deaths, hospital admissions, and emergency department visits across the Northeast.[23,25,26,27,28,29] For example, in the Northeast we can expect approximately 650 additional premature deaths per year from extreme heat by the year 2050 under either a lower (RCP4.5) or higher (RCP8.5) scenario and from 960 (under RCP4.5) to 2,300 (under RCP8.5) more premature deaths per year by 2090.[29]

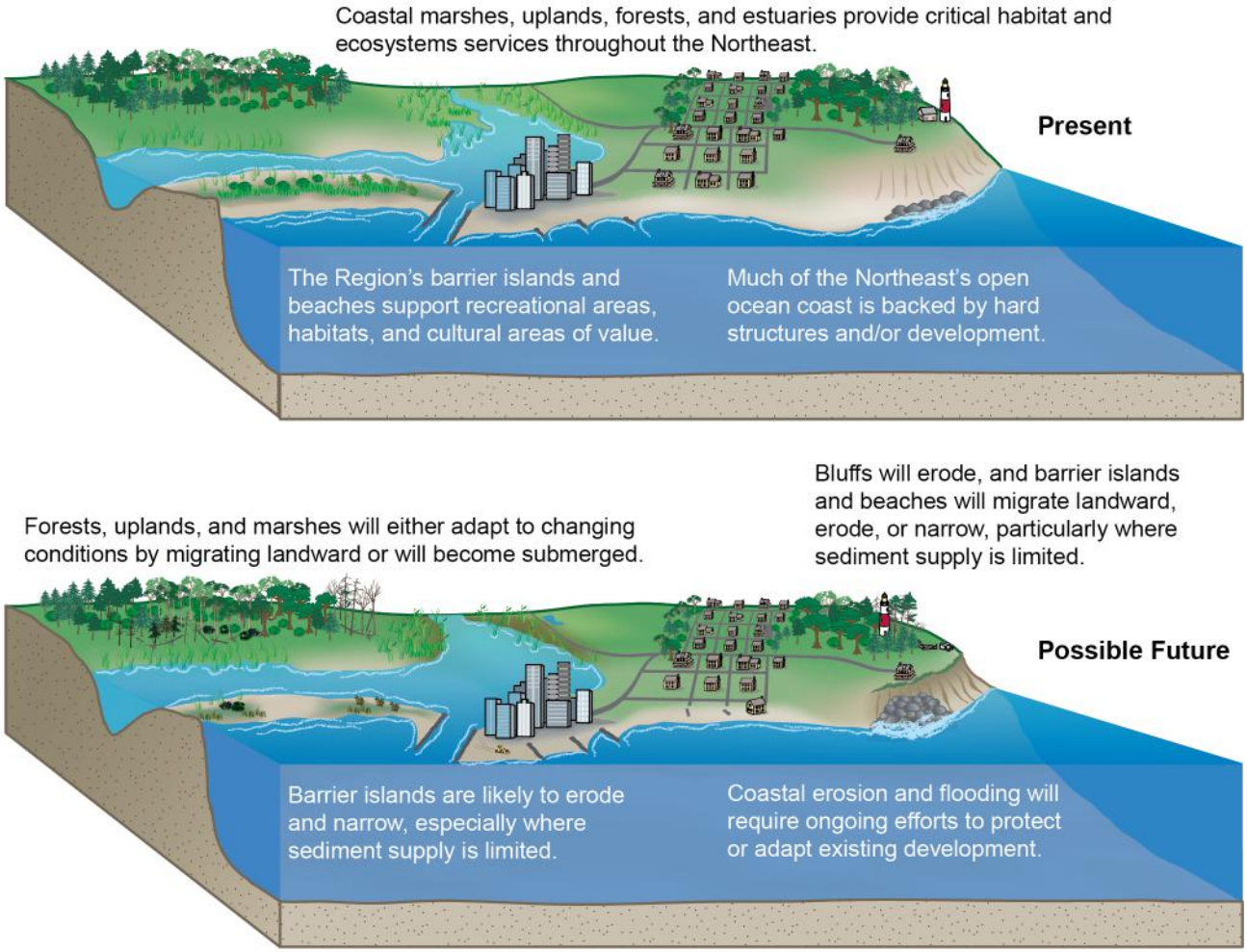
Communities, towns, cities, counties, states, and tribes across the Northeast are engaged in efforts to build resilience to environmental challenges and adapt to a changing climate. Developing and implementing climate adaptation strategies in daily practice often occur in collaboration with state and federal agencies (e.g., New Jersey Climate Adaptation Alliance 2017, New York Climate Clearinghouse 2017, Rhode Island STORMTOOLS 2017, EPA 2017, CDC 2015[30,31,32,33,34]). Advances in rural towns, cities, and suburban areas include low-cost adjustments of existing building codes and standards. In coastal areas, partnerships among local communities and federal and state agencies leverage federal adaptation tools and decision support frameworks (for example, NOAA's Digital Coast, USGS's Coastal Change Hazards Portal, and New Jersey's Getting to Resilience). Increasingly, cities and towns across the Northeast are developing or implementing plans for adaptation and resilience in the face of changing climate (e.g., EPA 2017[33]). The approaches are designed to maintain and enhance the everyday lives of residents and promote economic development. In some cities, adaptation planning has been used to respond to present and future challenges in the built environment. Regional efforts have recommended changes in design standards when building, replacing, or retrofitting infrastructure to account for a changing climate.

Lengthening of the Freeze-Free Period



These maps show projected shifts in the date of the last spring freeze (left column) and the date of the first fall freeze (right column) for the middle of the century (as compared to 1979–2008) under the lower scenario (RCP4.5; top row) and the higher scenario (RCP8.5; middle row). The bottom row shows the shift in these dates for the end of the century under the higher scenario. By the middle of the century, the freeze-free period across much of the Northeast is expected to lengthen by as much as two weeks under the lower scenario and by two to three weeks under the higher scenario. By the end of the century, the freeze-free period is expected to increase by at least three weeks over most of the region. *From Figure 18.3 (Source: adapted from Wolfe et al. 2018[35]).*

Coastal Impacts of Climate Change



(top) The northeastern coastal landscape is composed of uplands and forested areas, wetlands and estuarine systems, mainland and barrier beaches, bluffs, headlands, and rocky shores, as well as developed areas, all of which provide a variety of important services to people and species. (bottom) Future impacts from intense storm activity and sea level rise will vary across the landscape, requiring a variety of adaptation strategies if people, habitats, traditions, and livelihoods are to be protected. *From Figure 18.7 (Source: U.S. Geological Survey)*.

Background

The Northeast region is characterized by four distinct seasons and a diverse landscape that is central to the region's cultural identity, quality of life, and economic success. It is both the most heavily forested and most densely populated region in the country. Residents have ready access to beaches, forests, and other natural areas and use them heavily for recreation. Colorful autumn foliage, winter recreation, and summer vacations in the mountains or at the beach are all important parts of the Northeast's cultural identity, and this tourism contributes billions of dollars to the regional economy. The seasonal climate, natural systems, and accessibility of certain types of recreation are threatened by declining snow and ice, rising sea levels, and rising temperatures. By 2035, and under both lower and higher scenarios (RCP4.5 and RCP8.5), the Northeast is projected to be more than 3.6°F (2°C) warmer on average than during the preindustrial era. This would be the largest increase in the contiguous United States and would occur as much as two decades before global average temperatures reach a similar milestone.[36]

The region's oceans and coasts support a rich maritime heritage and provide an iconic landscape, as well as economic and ecological services. Highly productive marshes,[37,38] fisheries,[39,40] ecosystems,[41,42] and coastal infrastructure[43,44] are sensitive to changing environmental conditions, including shifts in temperature, ocean acidification, sea level, storm surge, flooding, and erosion. Many of these changes are already affecting coastal and marine ecosystems, posing increasing risks to people, traditions, infrastructure, and economies (e.g., Colburn et al. 2016[45]). These risks are exacerbated by increasing demands on these ecosystems to support human use and development. The Northeast has experienced some of the highest rates of sea level rise[46] and ocean warming[39] in the United States, and these exceptional increases relative to other regions are projected to continue through the end of the century.[47,48,49,50]

The Northeast is quite varied geographically, with a wide spectrum of communities including densely populated cities and metropolitan regions and relatively remote hamlets and villages (Figure 18.1). Rural and urban areas have distinct vulnerabilities, impacts, and adaptation responses to climate change.[51,52] The urbanized parts of the Northeast are dependent on the neighboring rural areas' natural and recreational services, while the rural communities are dependent on the economic vitality and wealth-generating capacity of the region's major cities. Rural and urban communities together are under increasing threat of climate change and the resulting impacts, and adaptation strategies reveal their interdependence and opportunities for successful climate resilience.[51] Rural–urban linkages[53,54,55] in the region could also be altered by climate change impacts.

In rural areas, community identity is often built around the prominence of small, multigenerational, owner-operated businesses and the natural resources of the local area. Climate variability can affect human migration patterns[56] and may change flows into or out of the Northeast as well as between rural and urban locations. Published research in this area, however, is limited. The Northeast has long been losing residents to other regions of the country.[57] Droughts and flooding can adversely affect ecosystem function, farm economic viability, and land use. Although future projections of major floods remain ambiguous, more intense precipitation events (Ch. 2: Climate, KM 6)[58] have increased the risk

of some types of inland floods, particularly in valleys, where people, infrastructure, and agriculture tend to be concentrated. With little redundancy in their infrastructure and, therefore, limited economic resilience, many rural communities have limited ability to cope with climate-related changes.

Population Density

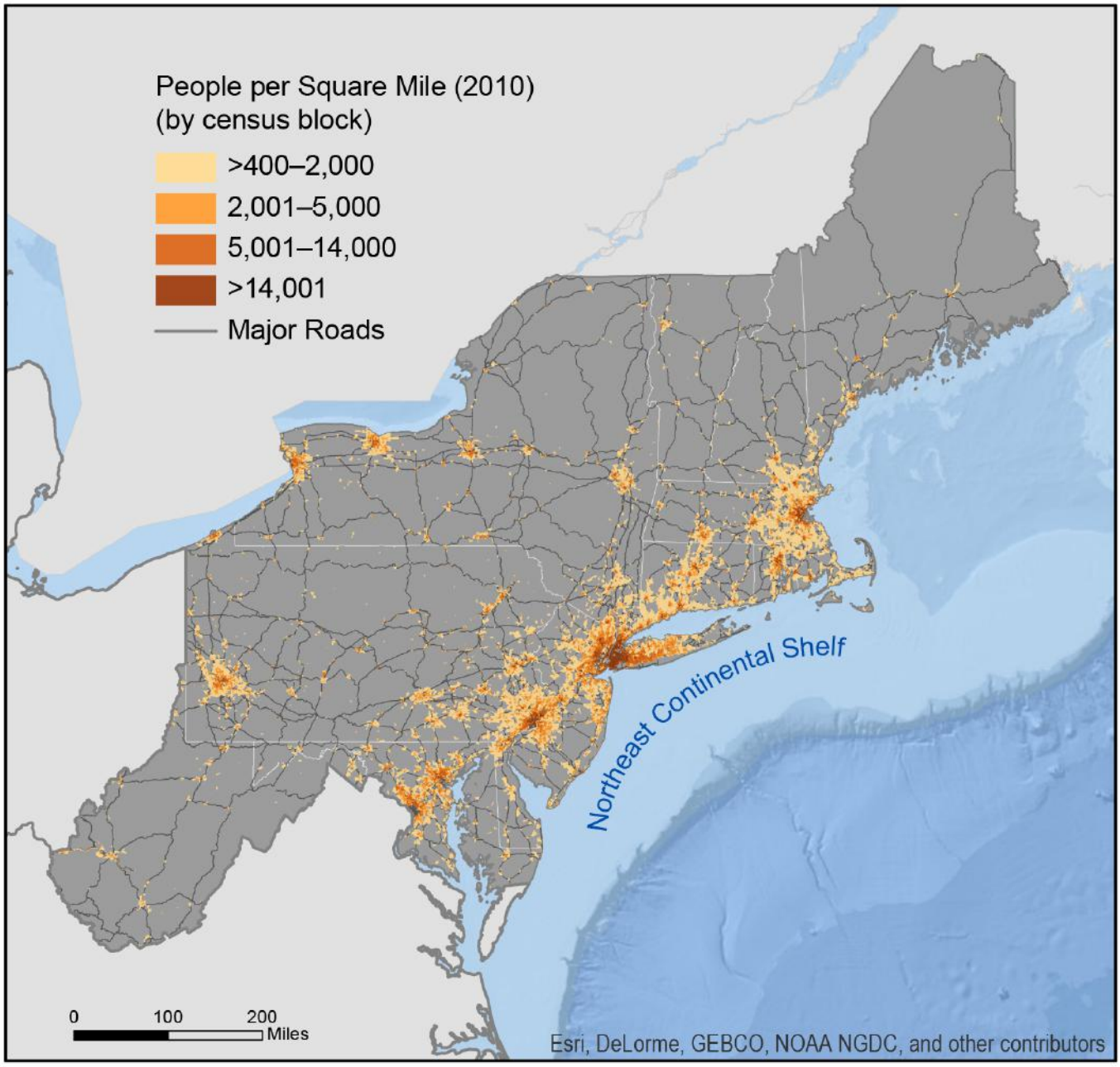


Figure 18.1: A satellite mosaic overlaid with primary roads and population density highlights the diverse characteristics of the region in terms of settlement patterns, interconnections among population centers of varying sizes, and variability in relief across the ocean shelf. Sources: U.S. Department of Transportation, U.S. Geological Survey, and ERT, Inc.

Residents in urban areas face multiple climate hazards, including temperature extremes, episodes of poor air quality, recurrent waterfront and coastal flooding, and intense precipitation events that can lead to increased flooding on urban streams. These physical changes may lead to large numbers of evacuated and displaced populations and damaged infrastructure; sustaining communities may require significant investment and planning to provide emergency response efforts, a long-term commitment to rebuilding and adaptation, and support for relocation. Underrepresented communities, such as the poor, elderly, language-isolated, and recent immigrants, are more vulnerable due to their limited ability to prepare for and cope with extreme weather and climate events.[59] Service infrastructure in the Northeast is at increasing risk of disruption, resulting in lower quality of life, economic declines, and enhanced social inequality.[17] Interdependencies across critical infrastructure sectors such as water, energy, transportation, and telecommunication (and related climate security issues) can lead to cascading failures during extreme weather and climate-related disruptions (Ch. 17: Complex Systems).[17,59,60] The region's high density of built environment sites and facilities, large number of historic structures, and older housing and infrastructure compared to other regions suggest that urban centers in the Northeast are particularly vulnerable to climate shifts and extreme weather events. For example, because much of the historical development of industry and commerce in New England occurred along rivers, canals, coasts, and other bodies of water, these areas often have a higher density of contaminated sites, waste management facilities, and petroleum storage facilities that are potentially vulnerable to flooding. As a result, increases in flood frequency or severity could increase the spread of contaminants into soils and waterways, resulting in increased risks to the health of nearby ecosystems, animals, and people—a set of phenomena well documented following Superstorm Sandy.[61,62,63]

The changing climate of the Northeast threatens the health and well-being of residents through environmental changes that lead to health-related impacts and costs, including additional deaths, emergency room visits and hospitalizations, higher risk of infectious diseases, lower quality of life, and increased costs associated with healthcare utilization. Health impacts of climate change vary across people and communities of the Northeast and depend on social, socioeconomic, demographic, and societal factors; community adaptation efforts; and underlying individual vulnerability (see Key Message 5) (see also Ch. 28: Adaptation).

Maintaining functioning, sustainable communities in the face of climate change requires effective adaptation strategies that anticipate and buffer impacts, while also enabling communities to capitalize upon new opportunities. Many northeastern cities already have or are rapidly developing short-term and long-term plans to mitigate climate effects and to plan for efficient investments in sustainable development and long-term adaptation strategies. Although timely adaptation to climate-related impacts would help reduce threats to people's health, safety, economic well-being, and ways of life, changes to those societal elements will not be avoided completely.

Key Message 1

Changing Seasons Affect Rural Ecosystems, Environments, and Economies

The seasonality of the Northeast is central to the region's sense of place and is an important driver of rural economies. Less distinct seasons with milder winter and earlier spring conditions are already altering ecosystems and environments in ways that adversely impact tourism, farming, and forestry. The region's rural industries and livelihoods are at risk from further changes to forests, wildlife, snowpack, and streamflow.

The distinct seasonality of the Northeast's climate supports a diverse natural landscape adapted to the extremes of cold, snowy winters and warm to hot, humid summers. This natural landscape provides the economic and cultural foundation for many rural communities, which are largely supported by a diverse range of agricultural, tourism, and natural resource-dependent industries (Ch. 10: Ag & Rural, KM 4).[1] The outdoor recreation industry contributes nearly $150 billion in consumer spending to the Northeast economy and supports more than one million jobs across the region.[64] Additionally, agriculture, fishing, forestry, and related industries together generate over $100 billion in economic activity annually, supporting more than half a million jobs in production and processing region-wide.[65] Projected changes in the Northeast's seasons will continue to affect terrestrial and aquatic ecosystems, forest productivity, agricultural land use, and other resource-based industries.[1] Alpine, freshwater aquatic, and certain forest habitats are most at risk.[66] Without efforts to mitigate climate change, warming winters and earlier spring conditions under a higher scenario (RCP8.5) will affect native ecosystems and the very character of the rural Northeast.[67]

Seasonal differences in Northeast temperature have decreased in recent years as winters have warmed three times faster than summers.[3] By the middle of this century, winters are projected to be milder still, with fewer cold extremes, particularly across inland and northern portions of the Northeast.[3] This will likely result in a shorter and less pronounced cold season with fewer frost days and a longer transition out of winter into the growing season.[68] Under the higher scenario (RCP8.5), the trend of decreasing seasonality continues for the northern half of the region through the end of the century, but by then summer temperatures across the Mid-Atlantic are projected to rise faster than those in winter.[4]

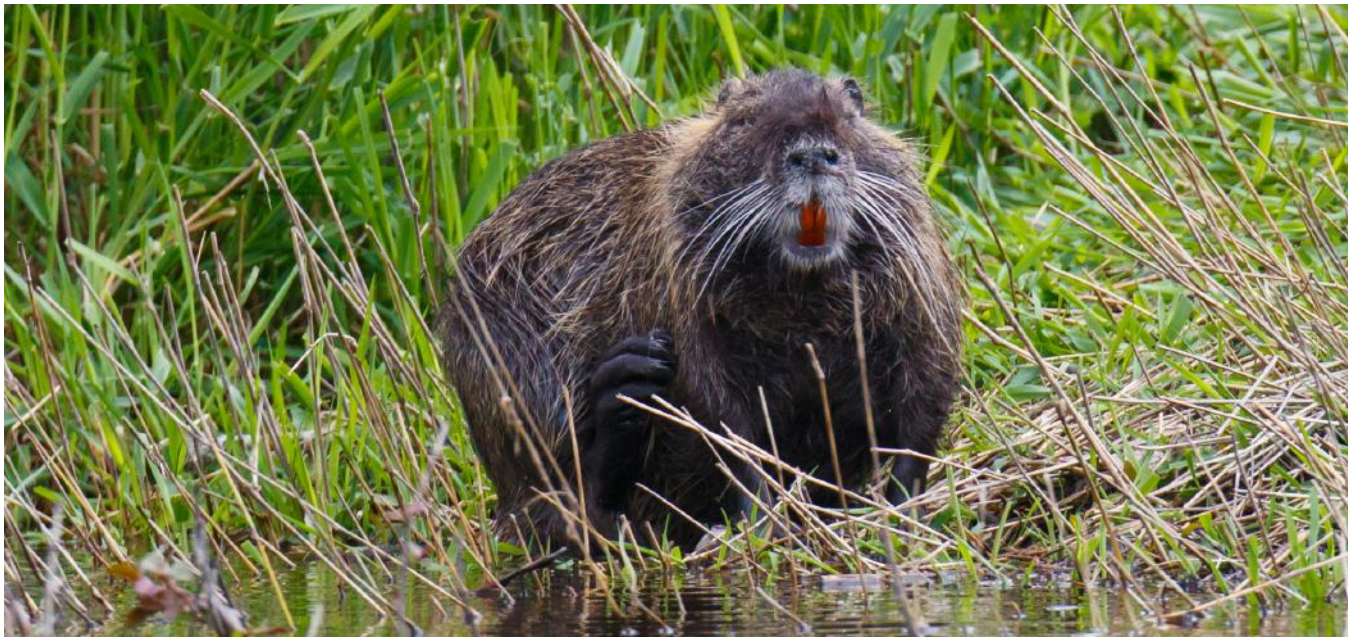
A Changing Winter–Spring Transition

Forests are already responding to the ongoing shift to a warmer climate, and changes in the timing of leaf-out affect plant productivity, plant–animal interactions, and other essential ecosystem processes.[69,70] Warmer late-winter and early-spring temperatures in the Northeast have resulted in trends towards earlier leaf-out and blooming, including changes of 1.6 and 1.2 days per decade, respectively, for lilac and honeysuckle (Ch. 7: Ecosystems, Figure 7.3).[71] The increase in growing season length is partially responsible for observed increases in forest growth and carbon sequestration.[72]

While unusual winter or early-spring warmth has caused plants to start growing and emerge from winter dormancy earlier in the spring, the increased vulnerability of species to subsequent cold spells is yet unknown. Early emergence from winter dormancy causes plants to lose their tolerance to cold temperatures and risk damage by temperatures they would otherwise tolerate. Early budbreak followed by hard freezes has led to widespread loss of fruit

crops and reduced seasonal growth of native tree species in the Northeast.[35,73]

Shifting seasonality can also negatively affect the health of forests (Ch. 6: Forests, KM 1) and wildlife, thereby impacting the rural industries dependent upon them. Warmer winters will likely contribute to earlier insect emergence[74] and expansion in the geographic range and population size of important tree pests such as the hemlock woolly adelgid, emerald ash borer, and southern pine beetle.[75,76,77] Increases in less desired herbivore populations are also likely, with white-tailed deer and nutria (exotic South American rodents) already being a major concern in different parts of the region.[78] According to State Farm Insurance,[79] motorists in West Virginia and Pennsylvania are already the first and third group of claimants most likely to file an insurance claim that is deer-related. Erosion from nutria feeding in lower Eastern Shore watersheds of Maryland has resulted in widespread conversion of marsh to shallow open water, changing important ecosystems that can buffer against the adverse impacts from climate change.[80] Species such as moose, which drive a multimillion-dollar tourism industry, are already experiencing increased parasite infections and deaths from ticks.[81,82,83] Warmer spring temperatures are associated with earlier arrivals of migratory songbirds,[84] while birds dependent upon spruce–fir forests in the northern and mountainous parts of the region are already declining and especially vulnerable to future change.[85] Northern and high-elevation tree species such as spruce and fir are among the most vulnerable to climate change in the Northeast.[70,86,87]



A nutria shows off its signature orange teeth. These large South American rodents are already a major concern in parts of the Northeast. Photo credit: ©Jason Erickson/iStock/Getty Images Plus.

Challenges for Natural Resource-Based Industries

Shorter, more moderate winters will present new challenges for rural industries. Poor surface and road conditions or washout have the potential to limit future logging operations, which need frozen or snow-covered soils to meet environmental requirements for winter operations.[70,88] Maple syrup production is linked to climate through potential shifts in sugar maple habitat,[89] tapping season timing and duration,[90,91] and the quality of both the trees and sap.[92,93] Climate change is making sugar maple tapping more challenging by increasing variability within and between seasons. Research into how the industry can adapt to these changes is ongoing.[89,94,95] With changes in weather and ecology come shifts in the cultural relationships to seasons as they have historically existed. Indigenous women from across these northeastern forests have come together to protect and sustain cultural traditions of the land they call Maple Nation. These climate impacts not only threaten the maple tree itself but also the seeds, soil, water, plants, and cultural lifeways that Indigenous peoples and tribal nations in the region associate with them.[96,97]

On the other hand, the impacts of warming on forests and ecosystems during the summer and autumn are less well understood.[98] In the summer, flowering in many agricultural crops and tree fruits is regulated in part by nighttime temperature, and growers risk lower yields as these temperatures rise.[35] Warmer autumn temperatures[98] influence processes such as leaf senescence (the change in leaf color as photosynthesis ceases), fruit ripening, insect phenology,[35] and the start of bird migration and animal hibernation.[99] October temperatures are the best predictor of leaf senescence in the northern hemisphere,[100] but other climatic factors can also shift the timing of autumn processes. Agricultural drought can advance leaf coloring and leaf drop, while abundant soil moisture can delay senescence.[101,102] Early frost events or strong winds can also result in sudden leaf senescence and loss.[98] Many deciduous trees are projected to experience an overall increase in their amount of autumn foliage color.[103]

As Northeast winters warm, scenarios project a combination of less early winter snowfall and earlier snowmelt, leading to a shorter snow season.[104,105] The proportion of winter precipitation falling as rain has already increased and will likely continue to do so in response to a northward shift in the snow–rain transition zone projected under both lower and higher scenarios (RCP4.5 and RCP8.5).[106,107,108] The shift in precipitation type and fewer days below freezing[3,4,35] are expected to result in fewer days with snow on the ground; decreased snow depth, water equivalent, and extent; an earlier snowmelt;[105,109,110] and less lake ice.[111] Warming during the winter–spring transition has already led to earlier snowmelt-related runoff in areas of the Northeast with substantial snowpack (Figure 18.2).[112] Earlier snowmelt-related runoff and lower spring peak streamflows in these areas are expected in the 2041–2095 period compared with the 1951–2005 period.[105]

Historical Changes in the Timing of Snowmelt-Related Streamflow

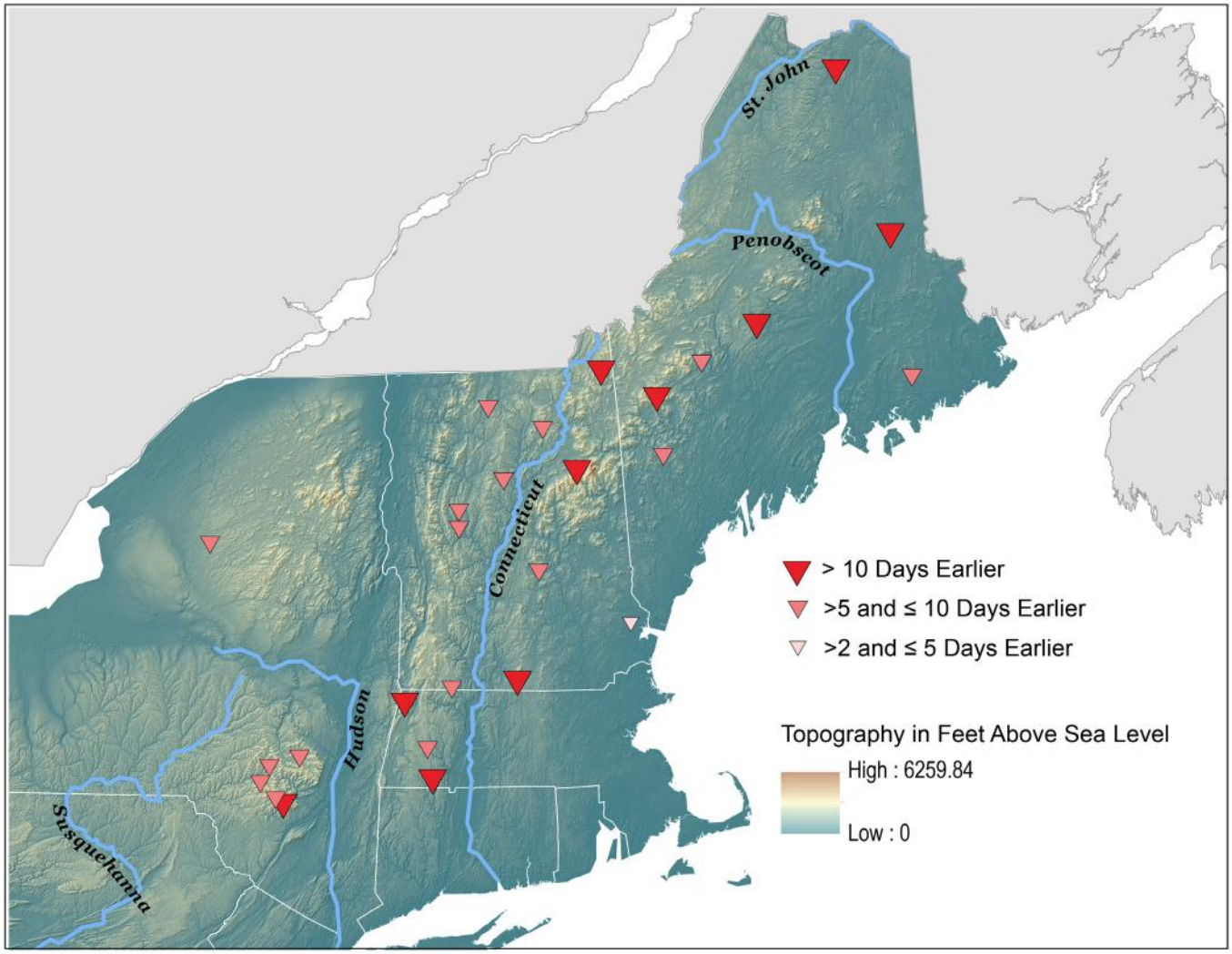


Figure 18.2: This map of part of the Northeast region shows consistently earlier snowmelt-related streamflow timing for rivers from 1960 to 2014. Each symbol represents the change for an individual river over the entire period. Changes in the timing of snowmelt potentially interfere with the reproduction of many aquatic species[113] and impact water-supply reservoir management because of higher winter flows and lower spring flows.[114] The timing of snowmelt-related streamflow in the Northeast is sensitive to small changes in air temperature. The average winter–spring air temperature increase of 1.67°F in the Northeast from 1940 to 2014 is thought to be the cause of average earlier streamflow timing of 7.7 days.[112] The timing of snowmelt-related streamflow is a valuable long-term indicator of winter–spring changes in the Northeast. Source: adapted from Dudley et al. 2017;[112] Digital Elevation Model CGIAR–CSI (CGIAR Consortium for Spatial Information). Reprinted with permission from Elsevier.

The Northeast winter recreation industry is an important economic resource for rural areas, supporting approximately 44,500 jobs and generating between $2.6–$2.7 billion in revenue annually.[115,116] Like other outdoor tourism industries, it is strongly influenced by weather and climate, making it particularly vulnerable to climate change.[116,117,118] Even under the lower scenario (RCP4.5), the average length of the winter recreation season and the number of recreational visits are projected to decrease by mid-century.[118] Under the same scenario, lost time for snowmaking is expected to delay the start of the ski season across southern areas, potentially impacting revenues during the winter holiday season. Activities that rely on natural snow and ice cover are projected to remain economically viable in only far northern parts of the region by end of century under the higher scenario (RCP8.5).[117,118]

Sensitivity to projected changes in winter climate varies geographically, and venues are adapting by investing in artificial snowmaking, opening higher-elevation trails, and offering a greater range of activities and services.[115,117] As the margin for an economically viable winter recreation season (a season with more than 100 days for skiing; more than 50 for snowmobiling) shifts northward and toward higher elevations, some affected areas will be able to extend their seasons with artificial snowmaking. However, the capacity of some vulnerable southern and low-elevation locations to adapt in the long term is expected to be limited by warming nighttime temperatures.[115,116,119] Markets farther north may benefit from a greater share of regional participation depending on recreationist preferences like travel time[118,120] and perceived snow cover conditions informed by local weather, referred to as the backyard effect.[121]

Intense Precipitation

The recent dominant trend in precipitation throughout the Northeast has been towards increases in rainfall intensity,[2,58] with recent increases in intensity exceeding those in other regions in the contiguous United States. Further increases in rainfall intensity are expected,[3] with increases in precipitation expected during the winter and spring with little change in the summer.[4] Monthly precipitation in the Northeast is projected to be about 1 inch greater for December through April by end of century (2070–2100) under the higher scenario (RCP8.5).[4]

Studies suggest that Northeast agriculture, with nearly $21 billion in annual commodity sales,[122] will benefit from the changing climate over the next half-century[35,123] due to greater productivity over a longer growing season (Figure 18.3) (see also Ch. 10: Ag & Rural). However, excess moisture is already a leading cause of crop loss in the Northeast.[35] Recent and projected increases in precipitation amount, intensity, and persistence[124,125] indicate increasing impacts on agricultural operations. Increased precipitation can result in soil compaction,[126] delays in planting, and reductions in the number of days when fields are workable.[127] If the trend in the frequency of heavy rainfall prior to the last frost continues, overly wet fields could potentially prevent Northeast farmers from taking full advantage of an earlier spring.[35] Increased soil erosion and agricultural runoff—including manure, fertilizer, and pesticides[128,129]—are linked to excess nutrient loading of water bodies as well as possible food safety or public health issues from food and waterborne infections.[130] Warmer winters are likely to increase livestock productivity in the Northeast[129] but are expected to also increase pressure from weeds and pests,[35] demand for pesticides,[128] and the risk of human health effects from increased chemical exposures.[130]

The projected changes in precipitation intensity and temperature seasonality would also affect streams and the biological communities that live in them. Freshwater aquatic ecosystems are vulnerable to changes in streamflow, higher temperatures, and reduced water quality.[131] Such ecosystems are especially vulnerable to increases in high flows, decreases in low flows, and the timing of snowmelt.[113,132,133] The impact of heavy precipitation on streamflows partly depends upon watershed conditions such as prior soil moisture and snowpack conditions, which vary throughout the year.[134,135,136,137] Although the annual minimum streamflows have increased during the last century,[138,139,140] late-summer warming[4,141] could lead to decreases in the minimum streamflows in the late summer and early fall by mid-century.[142]

Species that are particularly vulnerable to temperature and flow changes include stream invertebrates, freshwater mussels, amphibians, and coldwater fish.[66,131,143] For example, a recent study of the habitat suitable for dragonflies and damselflies (species that are a good indicator of ecosystem health along rivers) in the Northeast projected, under both the lower and higher scenarios (RCP4.5 and RCP8.5), habitat declines of 45%–99% by 2080, depending on the species.[144] Other particularly vulnerable groups include species with water-dependent habitats, such as salamanders and coldwater fish.[66,145] Increasing temperatures within freshwater streams threaten coldwater fisheries across northern New England and south through the Appalachian Mountains. A decrease in recreational fishing revenue is expected by end of this century under a higher scenario (RCP8.5) with the loss of coldwater habitat.[29,131,146]

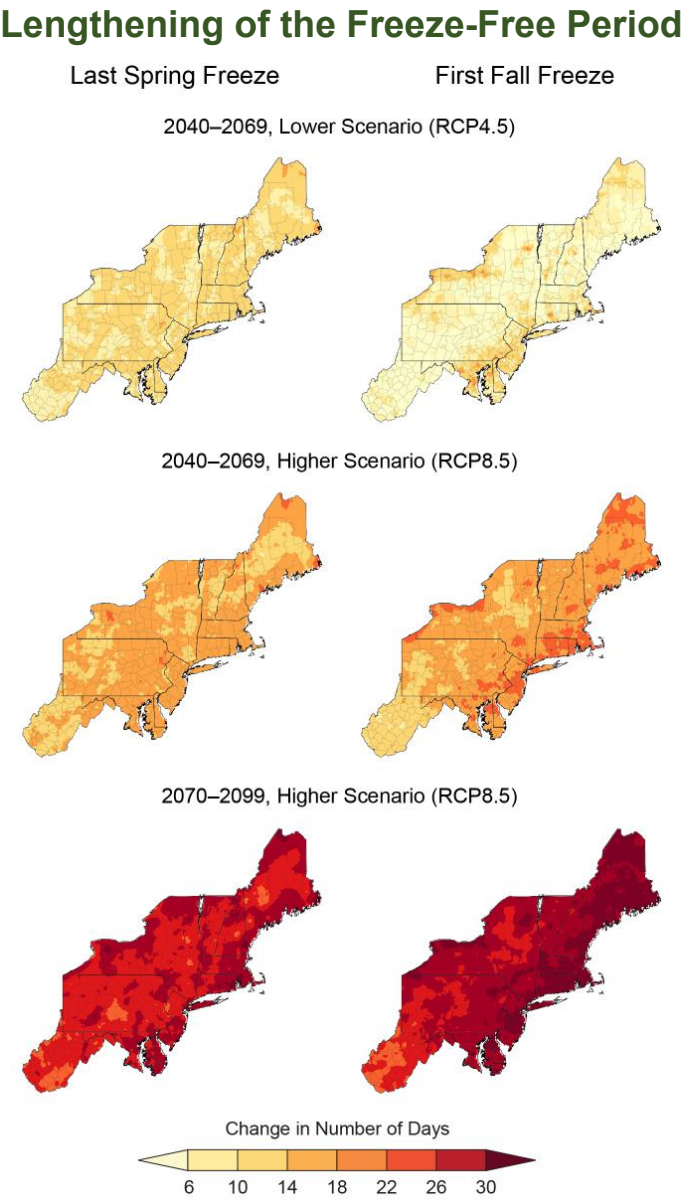


Figure 18.3: These maps show projected shifts in the date of the last spring freeze (left column) and the date of the first fall freeze (right column) for the middle of the century (as compared to 1979–2008) under the lower scenario (RCP4.5; top row) and the higher scenario (RCP8.5; middle row). The bottom row shows the shift in these dates for the end of the century under the higher scenario. By the middle of the century, the freeze-free period across much of the Northeast is expected to lengthen by as much as two weeks under the lower scenario and by two to three weeks under the higher scenario. By the end of the century, the freeze-free period is expected to increase by at least three weeks over most of the region. Source: adapted from Wolfe et al. 2018.[35]

Key Message 2

Changing Coastal and Ocean Habitats, Ecosystem Services, and Livelihoods

The Northeast's coast and ocean support commerce, tourism, and recreation that are important to the region's economy and way of life. Warmer ocean temperatures, sea level rise, and ocean acidification threaten these services. The adaptive capacity of marine ecosystems and coastal communities will influence ecological and socioeconomic outcomes as climate risks increase.

Ocean and coastal ecosystems are being affected by large changes in a variety of climate-related environmental conditions. These ecosystems support fishing and aquaculture,[5] tourism and recreation, and coastal communities.[6] They also provide important ecosystem services (benefits to people provided by the functions of various ecosystems), including carbon sequestration,[147] wave attenuation,[148,149] and fish[150] and shorebird[151] habitats. Observed and projected increases in temperature, acidification, storm frequency and intensity, and sea levels are of particular concern for coastal and ocean ecosystems, as well as local communities and their interconnected social and economic systems (Box 18.1).

Change in Sea Surface Temperature on the Northeast Continental Shelf

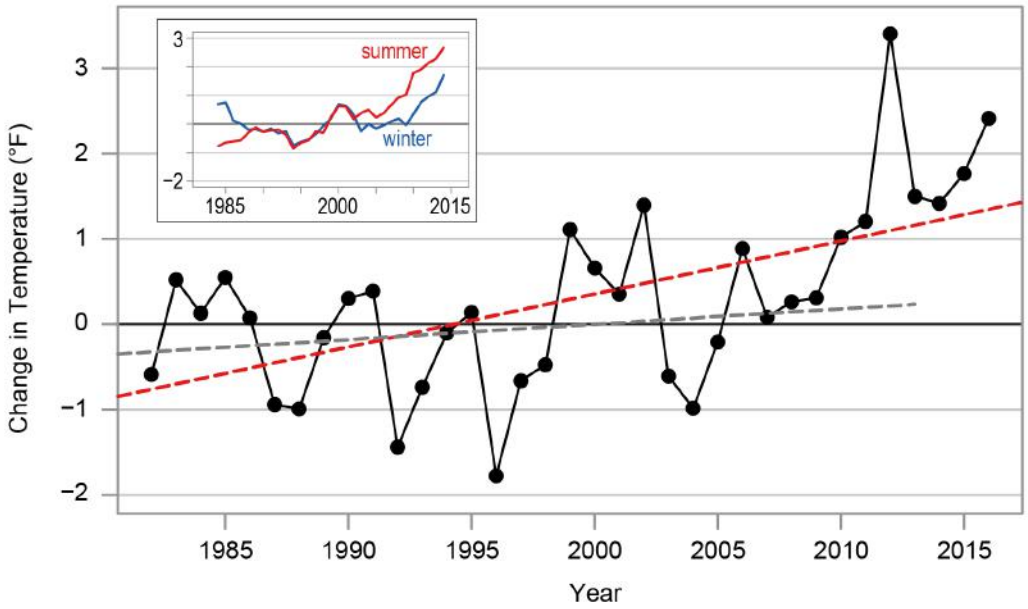


Figure 18.4: The figure shows annual average sea surface temperature (SST) differences from the 1982–2011 average (black dots and line). Over the period 1982–2016, sea surface temperature on the Northeast Continental Shelf has warmed at a rate of 0.06°F (0.033°C) per year (red dashed line). This rate is three times faster than the 1982–2013 global SST warming rate of 0.018°F (0.01°C) per year (gray dotted line).[39] The inset shows Northeast Continental Shelf seasonal SST differences from the 1982–2011 average as five-year rolling means for summer (July, August, September; red line) and winter (January, February, March; blue line). These seasons are centered on the warmest (summer) and coolest (winter) months for Northeast Shelf SSTs. Both seasons have warmed over the time period, but the summer warming rate has been stronger. Source: Gulf of Maine Research Institute.

Ocean Warming

Ocean and coastal temperatures along the Northeast Continental Shelf have warmed by 0.06°F (0.033°C) per year over the period 1982–2016 (Figure 18.4), which is three times faster than the 1982–2013 global average rate of 0.018°F (0.01°C) per year.[39] Over the last decade (2007–2016), the regional warming rate has been four times faster than the long-term trend, with temperatures rising 0.25°F (0.14°C) per year (Figure 18.4). Variability in ocean temperatures over the Northeast Continental Shelf (see Figure 18.1 for the location) has been related to the northern position of the Gulf Stream, the volume of water entering from the Labrador Current, and large-scale background warming of the oceans.[39,48,152,153] In addition to this warming trend, seasonality is also changing. Warming has been strongest during the summer months, and the duration of summer-like sea surface temperatures has expanded.[154] In parts of the Gulf of Maine, the summer-like season lengthened by two days per year since 1982, largely due to later fall cooling; the summer-like period expanded less rapidly (about 1 day per year) in the Mid-Atlantic, primarily due to earlier spring warming.[154]

Increasing temperatures and changing seasonality on the Northeast Continental Shelf have affected marine organisms and the ecosystem in various ways (Ch. 7: Ecosystems, KM 1; Ch. 9: Oceans). Seasonal ocean temperature changes have shifted characteristics of the spring phytoplankton blooms[158] and the timing of fish and invertebrate reproduction,[163,164] migration of marine fish that return to freshwater to spawn,[165,166] and marine fisheries.[155] As the timing of ecosystem conditions and biological events shifts, interactions between species and human activities such as fishing or whale watching will likely be affected.[42,155,163,166,167,168] These changes have the potential to affect economic activity and social features of fishing communities, working waterfronts, travel and tourism, and other natural resource-dependent local economies.

The warming trend experienced in the Northeast Continental Shelf has been associated with many fish and invertebrate species moving northward and to greater depths (Ch. 1: Overview, Figure 1.2h).[7,8,9,10,11] As these shifts have occurred, communities of animals present in a given area have changed substantially.[169] Species interactions can be affected if species do not shift at the same rate; generally, species groups appear to be moving together,[10] but overlap between pairs of specific species has changed.[42]

Rising ocean temperatures have also affected the productivity of marine populations. Species at the southern extent of their range, such as northern shrimp, surf clams, and Atlantic cod, are declining as waters warm,[39,170,171] while other species, such as black sea bass, are experiencing increased productivity.[11] Some species, such as American lobster and surf clam, have declined in southern regions where temperatures have exceeded their biological tolerances but have increased in northern areas as warming waters have enhanced their productivity.[40,171,172,173] The productivity of some harvested and cultured species may also be indirectly influenced by changing levels of marine pathogens and diseases. For example, increasing prevalence of shell disease in lobsters and several pathogens in oysters have been associated with rising water temperatures;[174,175] other pathogens that infect shellfish pose risks to human health (see Key Message 4).

Temperature-related changes in the distribution and productivity of species are affecting fisheries. Some fishermen now travel farther to catch certain species[176] or target new species that are becoming more prevalent as waters warm.[155] However, these types of responses do not always keep pace with ecosystem change due to constraints associated with markets, shoreside infrastructure, and regulatory limits such as access to quota licenses or permits.[177,178,179] In addition, stock assessment and fishery management processes do not explicitly account for temperature

influences on the managed species. In the case of Gulf of Maine cod, rising temperatures have been associated with changes in recruitment, growth, and mortality; failure to account for declining productivity as a result of warming led to catch advice that allowed for overfishing on the stock.[39,180] Proactive conservation and management measures can support climate resilience of fished species. For example, long-standing industry and management measures to protect female and large lobsters have supported the growth of the Gulf of Maine–Georges Bank stock

Box 18.1: Ocean Heat Wave Provides Glimpse of Climate Future

In 2012, sea surface temperatures on the Northeast Continental Shelf rose approximately 3.6°F (2°C) above the 1982–2011 average. This departure from normal was similar in magnitude to the changes projected for the end of the century under the higher scenario (RCP8.5) and represented the largest, most intense warm water event ever observed in the Northwest Atlantic Ocean (Ch. 9: Oceans).[155,156,157] This heat wave altered seasonal cycles of phytoplankton and zooplankton,[158,159] brought Mid-Atlantic fish species into the Gulf of Maine,[155] and altered the occurrence of North Atlantic right whales in the Gulf of Maine.[160] Commercial fisheries were also affected. A fishery for squid developed quickly along the coast of Maine, but the New England lobster fishery was negatively affected. Specifically, early spring warming triggered an early start of the fishing season, creating a glut of lobster in the supply chain and leading to a severe price collapse.[155] During 2012, the dockside price for lobster hit its lowest level in the past decade and dropped from an average per-pound value of $3.62 for June and July 2000–2011 to just $2.37 in those months in 2012. The experience during the 2012 ocean heat wave revealed vulnerabilities in the lobster industry and prompted a variety of adaptive responses, such as expanding processing capacity and further developing domestic and international markets[161] in an attempt to buffer against similar industry impacts in the future. Although an outlier when compared with our current climate, the ocean temperatures in 2012 were well within the range projected for the region by the end of the century under the higher scenario (RCP8.5).[162] The 2012 ocean heat wave provided a glimpse of impacts affecting ecological and social systems, and experiences during this event can serve as a stress test to guide adaptation planning in years to come (akin to 2015 in the Northwest) (see Ch. 24: Northwest, Box 24.7).

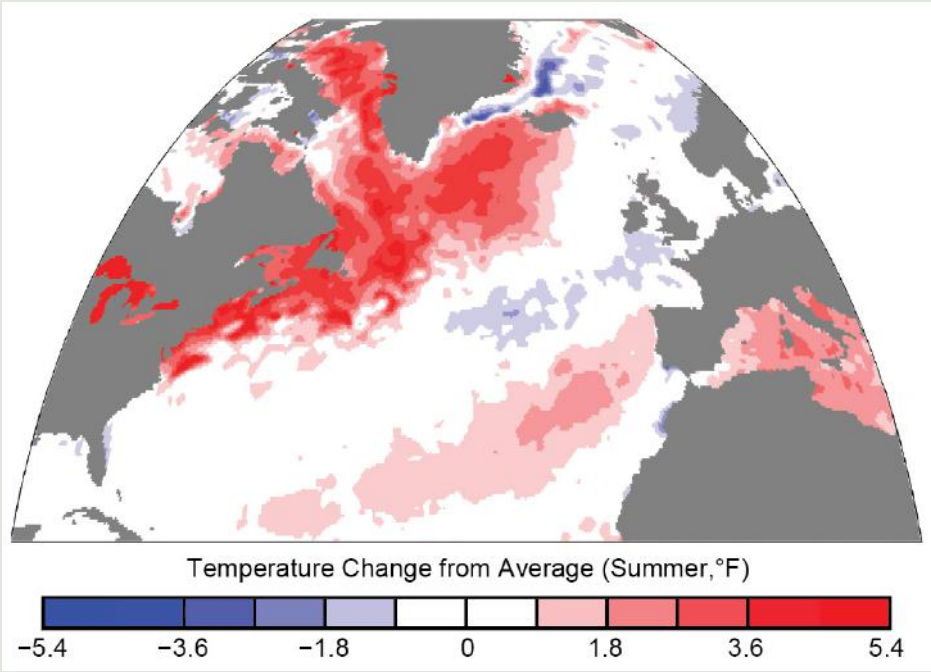


Figure 18.5: The map shows the difference between sea surface temperatures (SST) for June–August 2012 in the Northwest Atlantic and the average values for those months in 1982–2011.[155] While ocean temperatures during 2012 were exceptionally high compared to the current climate, they were within the range of end-of-century temperatures projected for the region under the higher scenario (RCP8.5). This heat wave affected the Northeast Continental Shelf ecosystem and fisheries, and similar extreme events are expected to become more common in the future (Ch. 9: Oceans). Source: adapted from Mills et al. 2013.[155] Reprinted with permission from Elsevier.

as waters warmed, but the lack of these measures in southern New England exacerbated declines in that stock as temperatures increased.[40]

Ocean Acidification

In addition to warming, coastal waters in the Northeast, particularly in the Gulf of Maine, are sensitive to the effects of ocean acidification because they have a low capacity for maintaining stable pH levels.[181,182] These waters are particularly vulnerable to acidification due to hypoxia (low-oxygen conditions)[183] and freshwater inputs, which are expected to increase as climate change progresses.[142,181,184] At the coastal margins, acidification is exacerbated by nutrient loading from land-based runoff and atmospheric deposition during heavy rainfall events. When added to the system, these nutrients promote the growth of algae that release carbon dioxide, which contributes to acidification, as they decay.[185]

Fisheries and aquaculture rely on shell-forming organisms that can suffer in more acidic conditions (Ch. 9: Oceans).[181,182,186] Some of the most valuable wild- and culture-based fisheries in the region harvest shelled organisms—including lobsters, scallops, blue crabs, oysters, surf clams, and mussels.[5] To date, there have been few studies of how local populations and different life stages will be affected by ocean acidification,[182] but actions taken by industry to counter the potential negative impacts are emerging. For example, when an oyster hatchery in Maine experienced low survival rates of larval oysters following exposure to low pH water during large runoff events, it collaborated with scientists to develop systems to monitor and control carbonate conditions in the facility (Ch. 9: Oceans).[187]

Future Projections of Ocean Warming and Acidification

Climate projections indicate that in the future, the ocean over the Northeast Continental Shelf will experience more warming than most other marine ecosystems around the world.[48,49] Continued warming and acidification are expected to further affect species and fisheries in the region. Future projections indicate that declines in the density of a zooplankton species, *Calanus finmarchicus*—an important food source for many fish and whales in the Northeast Shelf region—will occur as waters continue to warm through the end of the century.[188] Northward species distribution trends are projected to continue as ocean waters warm further.[189] A species vulnerability assessment indicated that approximately 50% of the commercial, forage, and protected fish and invertebrate species on the Northeast Continental Shelf will be highly or very highly vulnerable to climate change through 2050 under the higher scenario (RCP8.5).[143] In general, species in the southern portion of the region are expected to remain stable through mid-century, but many species in the northern portion are expected to be negatively affected by warming and acidification over that timeframe.[143,186] Species population models projected forward under future ocean conditions also indicate declines of species that support some of the most valuable and iconic fisheries in the Northeast, including Atlantic cod,[39,190] Atlantic sea scallops,[191] and American lobster.[40] In addition, species that are already endangered and federally protected in the Northeast—such as Atlantic sturgeon, Atlantic salmon, and right whales—are expected to be further threatened by climate change.[192,193,194,195]

Changes in Distribution and Abundance of Marine Species

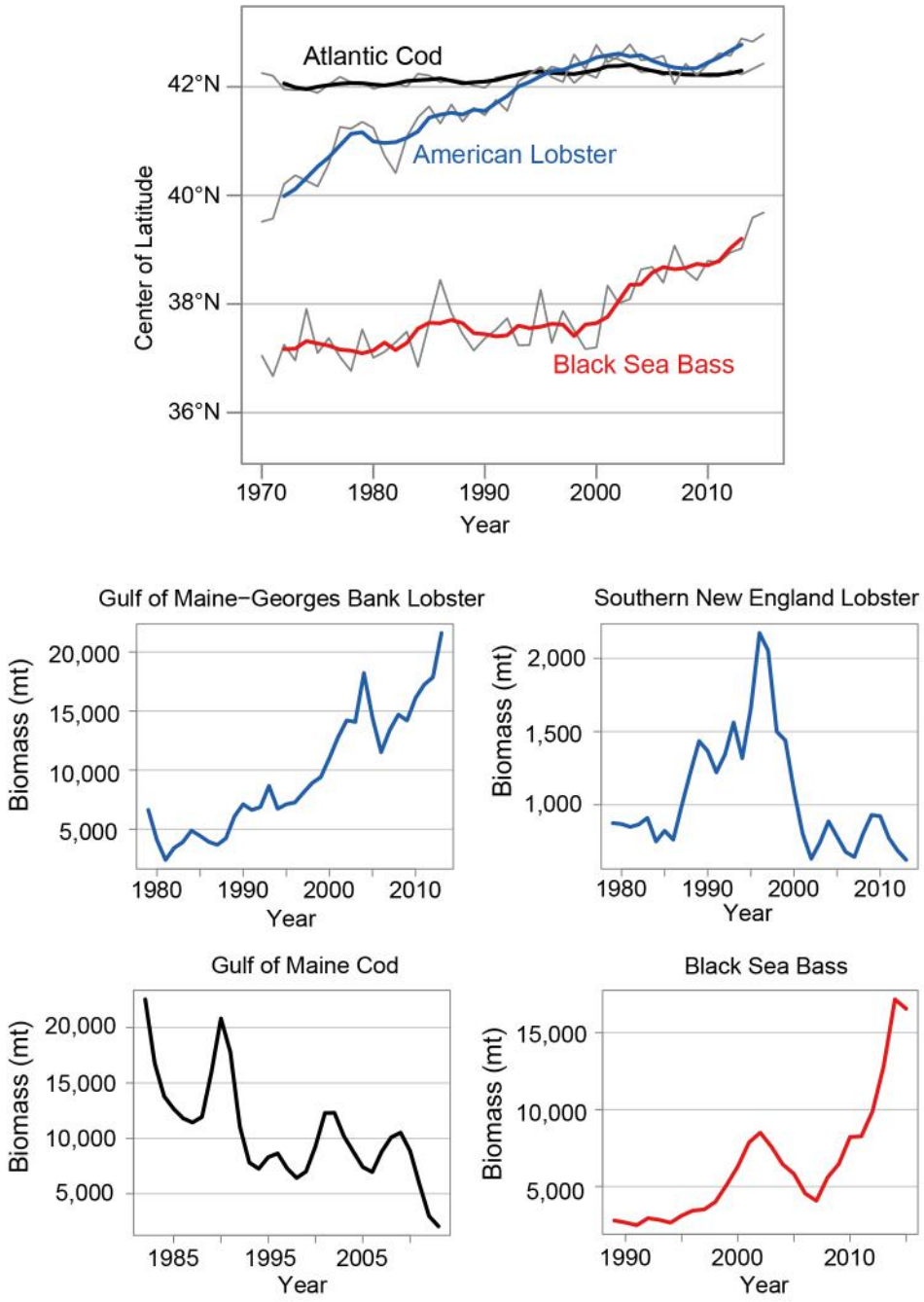


Figure 18.6: The figure shows changes over time in geographic distribution (top panel) and biomass (four bottom panels) for various marine species along the Northeast Shelf. As waters in the region have warmed, the spatial distributions of many fish species have been shifting northward, while population trends of several marine species show more variability over time. The top panel shows shifts in spatial distribution over time for select fish species, based on their latitudinal centers of biomass. The four panels on the bottom show biomass estimates for the same marine resource stocks. Gulf of Maine cod, a coldwater species, has not shifted in location but has declined in biomass, while black sea bass (a warmwater species) has moved northward and increased in biomass as waters have warmed. The lobster distribution shift reflects declines in productivity of the southern stock and increasing biomass of the northern stock. Sources: (black sea bass) adapted from Northeast Fisheries Science Center 2017;[204] (all others) Gulf of Maine Research Institute.

A number of coastal communities in the Northeast region have strong social and cultural ties to marine fisheries, and in some communities, fisheries represent an important economic activity as well.[196,197] Future ocean warming and acidification, which are expected under all scenarios considered, would affect fish stocks and fishing opportunities available to coastal communities. Fisheries targeting species at the southern extent of their range have already experienced substantial declines in landings with rising ocean temperatures,[170,173,198,199,200] and this pattern is projected to continue in the future (e.g., Cooley et al. 2015, Pershing et al. 2015, Le Bris et al. 2018[39,40,191]). Fishers may need to travel farther to fishing locations for species they currently catch,[189] increasing fuel and crew costs. Distribution shifts (Figure 18.6) can also create opportunities to target new species moving into an area.[155] The impacts and opportunities associated with these changes will not be evenly shared within or among fisheries, fleets, or communities; as such, adaptation may alter social dynamics, cultural ties, and economic benefits.[201,202,203]

Sea Level Rise, Storms, and Flooding

Along the Mid-Atlantic coast (from Cape Hatteras, North Carolina, to Cape Cod, Massachusetts), several decades of tide gauge data through 2009 have shown that sea level rise rates were three to four times higher than the global average rate.[46,205,206] The region's sea level rise rates are increased by land subsidence (sinking)—largely due to vertical land movement related to the melting of glaciers from the last ice age—which leaves much of the land in this region sinking with respect to current sea level.[47,207,208,209] Additionally, shorter-term fluctuations in the variability of ocean dynamics,[210,211] atmospheric shifts,[212,213] and ice mass loss from Greenland and Antarctica[214] have been connected to these recent accelerations in the sea level rise rate in the region. For example, a slowdown of the Gulf Stream during a shorter period of extreme sea level rise observed over 2009–2010 has been linked to a weakening of the Atlantic meridional overturning circulation—the northward flow of upper-level warm, salty waters in the Atlantic (including the Gulf Stream current) and the southward flow of colder, deeper waters.[215] These higher-than-average rates of sea level rise measured in the Northeast have also led to a 100%–200% increase in high tide flooding in some places, causing more persistent and frequent (so-called nuisance flooding) impacts over the last few decades.[44,47,216,217]

Coastal flood risks from storm-driven precipitation and surges are major drivers of coastal change[218,219] and are also amplified by sea level increases.[217,220,221] Storms have unique climatological features in the Northeast—Nor'easters (named for the low-pressure systems typically impacting New England and the Mid-Atlantic with strong northeasterly winds blowing from the ocean over coastal areas) typically occur between September and April, and when coupled with the Atlantic hurricane season between June and September, the region is susceptible to major storms nearly year-round. Storm flood heights driven by hurricanes in New York City increased by more than 3.9 feet (1.2 m) over the last thousand years.[14] When coupled with storm surges, sea level rise can pose severe risks of flooding, with consequent physical and mental health impacts on coastal populations (see Key Messages 4 and 5).

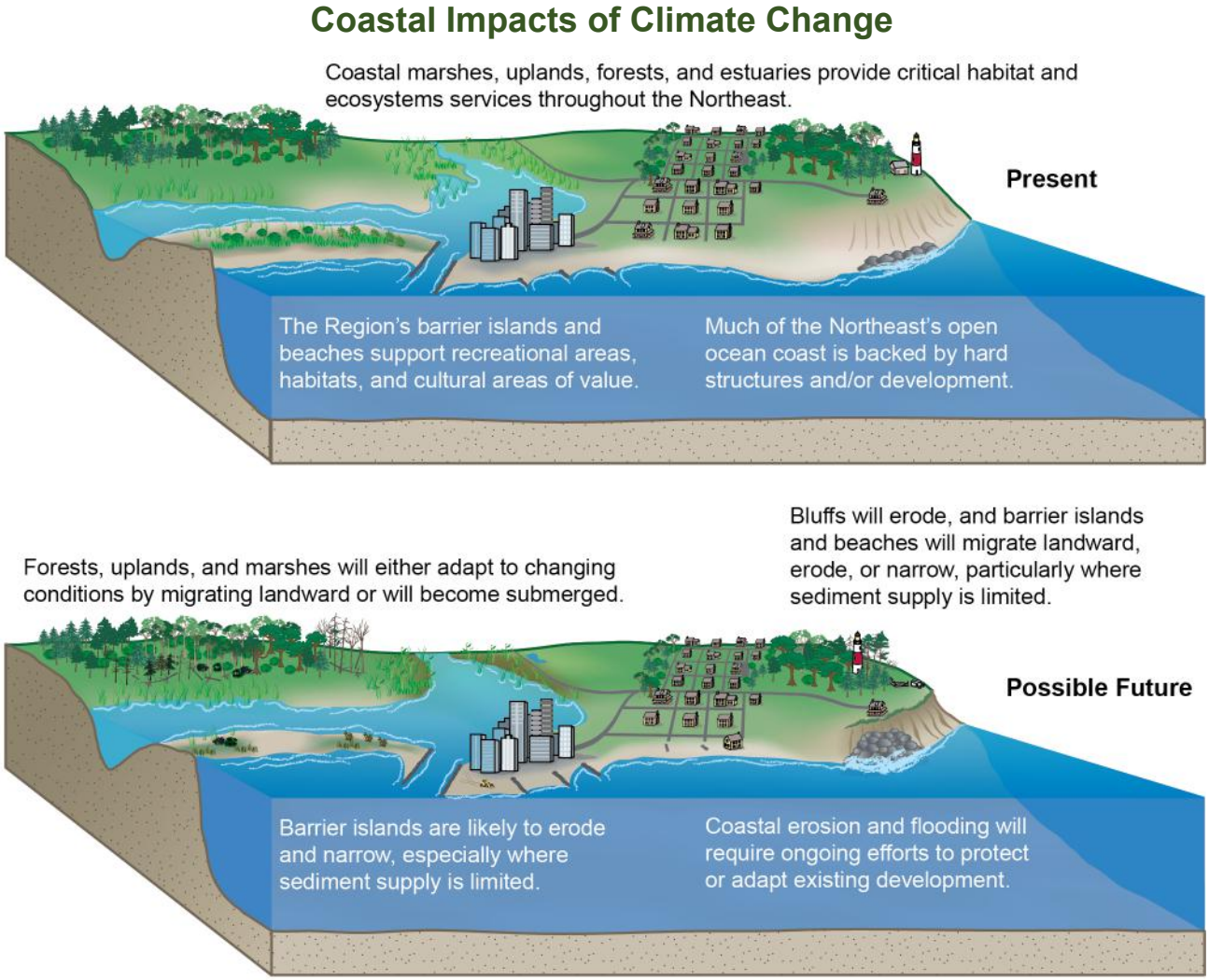


Figure 18.7: (top) The northeastern coastal landscape is composed of uplands and forested areas, wetlands and estuarine systems, mainland and barrier beaches, bluffs, headlands, and rocky shores, as well as developed areas, all of which provide a variety of important services to people and species. (bottom) Future impacts from intense storm activity and sea level rise will vary across the landscape, requiring a variety of adaptation strategies if people, habitats, traditions, and livelihoods are to be protected. Source: U.S. Geological Survey.

Landscape Change and Impacts on Ecosystems Services

Because of the diversity of the Northeast's coastal landscape, the impacts from storms and sea level rise will vary at different locations along the coast (Figure 18.7).[12,13] Rocky and heavily developed coasts have limited infiltration capacity to absorb these impacts, and thus, these low-elevation areas will become gradually inundated.[222,223] However, more dynamic environments, such as mainland and barrier beaches, bluffs, and coastal wetlands, have evolved over thousands of years in response to physical drivers. Such responses include erosion, overwashing, vertical accretion (increasing elevation due to sediment movement), flooding in response to storm events,[218,224,225] and landward migration over the longer term as sea level has risen.[226] Uplands, forests, and agricultural lands can provide transitional areas for these more dynamic settings, wherein the land gradually converts to a tidal marsh.

Varied ecosystem services and natural features have long attracted and sustained people along the coast of the Northeast region. Ecosystem services—including the provisioning of

groundwater resources, the filtering of non-point source pollution, sequestering carbon, mitigating storm impacts and erosion, and sustaining working waterfronts and cultural features such as iconic regional landscapes, recreation, and traditions—are facing multiple climate threats. Marshes and beaches serve as the first line of defense for coastal property and infrastructure in the face of storms.[227] They also provide critical habitat for a variety of migratory shorebirds and, when combined with nearshore seagrass and estuaries, serve as nurseries for many commercial marine species.[37,38,150,151,228,229] Regional marshes trap and store carbon[147,230,231,232] and help to capture non-point source pollution before it enters seawater.[233,234,235] Regional beaches are important tourist and recreational attractions, and many coastal national parks and national historic sites throughout the region help preserve cultural heritage and iconic coastal landscapes.[236,237] The Northeast coast is also home to many Indigenous peoples whose traditions and ways of life are deeply tied to land and water (Box 18.2). Coastal tribes often have limited resources, infrastructure, and land ownership, and these limitations can worsen the impacts of climate change and prohibit relocation (Ch. 15: Tribes, KM 1 and 3).

Box 18.2: Indigenous Peoples and Tribal Nations

Indigenous peoples and tribal nations of the Northeast region have millennia-long relationships with the diverse landscapes and climate zones found throughout the region.[238,239,240] Currently, for the 18 federally recognized, numerous state-recognized, and federally unrecognized tribal nations of the Northeast,[241,242] the challenges of adapting to a changing climate add additional uncertainty to existing efforts for reclamation of land and sovereignty and the revitalization of languages and cultures (Ch. 15: Tribes, KM 1 and 3).[97,243] However, in response to a regional shift in the seasons, there has been an increase in climate adaptation work by tribes over the last decade (Ch.15: Tribes, Figure 15.1). These projects have been framed by Indigenous knowledges to address impacts to culturally and economically important resources and species, such as brown ash, sweetgrass, forests, and sugar maple, as well inland and ocean fisheries.[238,244,245,246] These projects provide important results for the tribal nations themselves but could also provide examples of adaptation and survival for other tribal nations and non-tribal communities to consider as they work towards a deeper and more complex engagement to address future landscapes.[97,240] Although not all tribally led climate research and projects across regions have been reported or published, there are even fewer publicly available examples in the Northeast region, and especially for state-recognized and unrecognized tribes. This seems to present itself as a potential future research opportunity for tribal engagement and collaborations in the Northeast (Ch. 15: Tribes).[97]

Projections of Future Sea Level Rise and Coastal Flooding

Projections for the region suggest that sea level rise in the Northeast will be greater than the global average of approximately 0.12 inches (3 mm) per year.[247,248] According to Sweet et al. (2017),[47] the more probable sea level rise scenarios—the Intermediate-Low and Intermediate scenarios from a recent federal interagency sea level rise report (App. 3: Data & Scenarios)—project sea level rise of 2 feet and 4.5 feet (0.6 m and 1.4 m) on average in the region by 2100, respectively.[47] The worst-case and lowest-probability scenarios, however, project that sea levels in the region would rise upwards of 11 feet (3 m) on average by the end of the century.[47] The higher projections for the region as compared with most others in the United States are due to continued changes in oceanic and atmospheric dynamics, thermal expansion, ice melt contributions from Greenland and Antarctica, and ongoing subsidence in the region due to tectonics and non-tectonic effects such as groundwater withdrawal.[47,50,249,250,251,252] Furthermore, the strongest hurricanes are anticipated to become both more frequent and more intense in the future, with greater amounts of precipitation (Ch. 2: Climate, Box 2.5).[50,253,254,255] Thirty-two percent of open-coast north and Mid-Atlantic beaches are predicted to overwash during an intense future nor'easter type storm,[256] a number that increases to more than 80% during a Category 4 hurricane.[257,258]

Future Adaptability of the Coastal Landscape

The dynamic ability of coastal ecosystems to adapt to climate-driven changes depends heavily upon sufficient sediment supply, elevation and slope, barriers to migration,[225] tidal restrictions, wave climatology,[219,259] and the rates of sea level rise. Although nearly 70% of the Northeast coast has some physical ability to dynamically change,[13] an estimated 88% of the Northeast population lives on developed coastal landforms that have limited ability to naturally adapt to sea level rise.[260] Built infrastructure along the coast, such as seawalls, bulkheads, and revetments, as well as natural barriers, such as coastal bluffs, limits landward erosion; jetties and groins interrupt alongshore sediment supply; and culverts and dams create tidal restrictions that can limit habitat suitability for fish communities (see Figure 18.7).[261] An estimated 26% of open ocean coast from Maine to Virginia contains engineering structures.[262] While these structures can help mitigate hazards to people and property, they also reduce the land area for ecosystem migration, as well as the adaptive capacity of natural coastal environments.[43,227,263,264] The ability of marshes in the region to respond to sea level-induced change varies by location, with some areas increasing in elevation, experiencing vegetation shifts, and/or expanding in extent while others are not.[265,266,267,268,269,270,271] Forest diebacks, or "ghost forests," due to wetland encroachment[70,272] are being observed in southern New Jersey and Maryland (Figure 18.8), although one study found that southern New England forests are not showing similar signs of dieback.[273]

Forest Dieback Due to Sea Level Rise

Figure 18.8: Atlantic white cedars dying near the banks of the Bass River in New Jersey show wetland encroachment on forested areas. Photo credit: Ted Blanco/Climate Central.

Projected changes in climate will threaten the integrity of coastal landforms and ecosystems that provide services people and animals rely on and that act as important natural buffers to hazards. Under more extreme scenarios (such as the higher scenario, RCP8.5), marshes are unlikely to survive and, thus, would convert to open water.[224,274,275] At lower rates of sea level rise, marsh health will depend heavily upon site-specific hydrologic, physical, and sediment supply conditions.[259,275,276,277,278] Long-term coastal erosion, as driven by sea level rise and storms, is projected to continue, with one study finding the shoreline likely to erode inland at rates of at least 3.3 feet (1 m) per year among 30% of sandy beaches along the U.S. Atlantic coast.[279] Continued increases in the rate of sea level rise—on the order of 0.08 inches (2 mm) per year above the 20th-century rate—could cause much of the open ocean coasts in the Mid-Atlantic to transition to a state wherein coastal barrier systems migrate landward more rapidly, experience reductions in width or height, and overwash and breach more frequently.[280] Such an increase is projected to occur this century under the Intermediate-Low scenario, which suggests that global sea levels will rise approximately 0.24 inches (6 mm) per year.[47]

An ongoing challenge, now and in the future, is to adequately account for and determine the monetary value of the ecosystem services provided by marine and coastal environments[6,41,281] and to adaptively manage the ecosystems to achieve targets that are responsive to both development and conservation.[282]

These changes to the coastal landscape would threaten the sustainability of communities and their livelihoods. Historical settlement patterns and ongoing development combine to increase the regional vulnerability of coastal communities to sea level rise, coastal storms, and increased inundation during high tides and minor storms. For example, estimates of coastal property losses and protective investments through 2100 due to sea level rise and storm surge vary from less than $15 billion for southeastern Massachusetts to in excess of $30 billion for coastal New Jersey and Delaware under either the lower (RCP4.5) or higher (RCP8.5) scenarios (discounted at 3%).[29] Saltwater intrusion can also impact drinking water supplies, including the alteration of groundwater systems.[283,284] A growing area of research explores potential migration patterns in response to climate-related coastal impacts, where coastal states such as Massachusetts, New Jersey, and New York are anticipated to see large outflows of migrants, a pattern that would stress regional locations further inland.[285] In addition to property and infrastructure impacts (Key Message 3), the facilities and cultural resources that support coastal tourism and recreation (such as parking lots, pavilions, and boardwalks), as well as cultural landscapes and historic structures,[236,237] will be at increased risk from high tide flooding, storm surge, and long-term inundation. In some locations, these culturally and socially important structures also support economic activity; for example, many fishing communities rely on small docks and other shoreside infrastructure for their fishing operations, increasing the risk of substantial disruption if they are lost to sea level rise and increasing storm frequency.[45,286]

Key Message 3

Maintaining Urban Areas and Communities and Their Interconnectedness

The Northeast's urban centers and their interconnections are regional and national hubs for cultural and economic activity. Major negative impacts on critical infrastructure, urban economies, and nationally significant historic sites are already occurring and will become more common with a changing climate.

Climate–Infrastructure Interaction and Heightened Risks

Northeastern cities, with their abundance of concrete and asphalt and relative lack of vegetation, tend to have higher temperatures than surrounding regions due to the urban heat island effect (increased temperatures, typically measured during overnight periods, in highly urbanized areas in comparison to outlying suburban, exurban, and rural locations). During extreme heat events, nighttime temperatures in the region's big cities are generally several degrees higher than surrounding regions, leading to higher risk of heat-related death. In urban areas, the hottest days in the Northeast are also often associated with high concentrations of urban air pollutants including ground-level ozone (Ch. 13: Air Quality, KM 1). This combination of heat stress and poor urban air quality can pose a major health risk to vulnerable groups: young children, elderly, socially or linguistically isolated, economically disadvantaged, and those with preexisting health conditions, including asthma. Vulnerability is further heightened as key infrastructure, including electricity for air conditioning, is more likely to fail precisely when it is most needed—when demand exceeds available supply—with the potential for substantial negative health consequences.[287]

Finally, vulnerability to heat waves is not evenly distributed throughout the region. Rather, outdoor versus indoor air temperatures, baseline health, occupation, and access to air conditioning are important determinants of vulnerability (see Key Message 4).

Urban areas are at risk for large numbers of evacuated and displaced populations and damaged infrastructure due to both extreme precipitation events and recurrent flooding, potentially requiring significant emergency response efforts and consideration of long-term commitment to rebuilding and adaptation, and/or support for relocation where needed. Poor, elderly, historically marginalized, recent immigrants, and linguistically or socially isolated individuals as well as those populations with existing health disparities are more vulnerable to precipitation events and flooding due to a limited ability to prepare for and cope with such events.[59]

Critical Infrastructure Service Disruption

Much of the infrastructure in the Northeast, including drainage and sewer systems, flood and storm protection assets, transportation systems, and power supply, is nearing the end of its planned life expectancy. Current water-related infrastructure in the United States is not designed for the projected wider variability of future climate conditions compared to those recorded in the last century (Ch. 3: Water, KM 2). In order to make Northeast systems resilient to the kind of extreme climate-related disruptions the region has experienced recently—and the sort of disruptions projected for the future—would require significant new investments in infrastructure. For example, in Pennsylvania, bridges are expected to be more prone to damage during extreme weather events, because the state leads the country in the highest percentage of structurally deficient bridges.[288] Pennsylvania's water treatment and wastewater systems are also notably aging, requiring an estimated $28 billion in new

investment over the next 20 years for repairs and to meet increasing demands.[288]

Climate-related disruptions will only exacerbate existing issues with aging infrastructure. Sea level rise has amplified storm impacts in the Northeast region (Key Message 2), contributing to higher surges that extend further inland, as demonstrated in New York City.[14,15,16] Sea level rise is leading to an increase in the frequency of coastal flooding, a trend that is projected to grow for cities such as Baltimore and Washington, DC.[289] High tide flooding has increased by a factor of 10 or more over the last 50 years for many cities in the Northeast region and will become increasingly synonymous with regular inundation, exceeding 30 days per year for an estimated 20 cities by 2050 even under a very low scenario (RCP2.6).[216] More frequent high tide flooding (also referred to as nuisance, or sunny day, flooding) will be experienced at low-elevation cities and towns in the region (Figure 18.9). Sea level rise (see Key Message 2) under higher scenarios will likely increase property losses from hurricanes and other coastal storms for the region by $6–$9 billion per year by 2100, while changes in hurricane activity could raise these estimates to $11–$17 billion per year.[260] In other words, projected future costs are estimated to continue along a steep upward trend relative to what is being experienced today. However, there is limited published research that quantifies the costs associated with increased damage across an entire system in response to amplified storm events. Actions to replace and/or significantly modify the Northeast's aging infrastructure provide opportunities to incorporate climate change adaptation and resilience into standard capital upgrades, reducing these future costs.

Mitigation in the Northeast

The Northeast region has traditionally been a leader in greenhouse gas mitigation action, serving as a potential model for other states. The Regional Greenhouse Gas Initiative is the first mandatory market-based program in the United States to cap and reduce CO_2 emissions from the power sector through a cooperative effort among Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont.

King Tide Flooding in Northeast

Figure 18.9: The photo shows king tide flooding on Dock Street in Annapolis, Maryland, on December 21, 2012. Photo credit: Amy McGovern (CC BY 2.0).

Impacts on Urban Economies

Service and resource supply infrastructure in the Northeast region is at increasing risk of disruption, resulting in lower quality of life, economic declines, and increased social inequality.[17] Loss of public services affects the capacity of communities to function as administrative and economic centers and triggers disruptions of interconnected supply chains (Ch. 16: International, KM 1). Interdependencies across critical infrastructure sectors such as water, energy, transportation, and telecommunication can lead to cascading failures during extreme weather and climate-related disruptions,[17,59] as occurred during the 2003 blackout in New York City (Ch. 17: Complex Systems, Box 17.5; Ch. 11: Urban). For example, the Northeast is projected to experience a significant increase in summer heat and the number and/or duration of heat waves that will further stress summertime energy peak

load demands from higher air conditioning use and the greater need to pump and treat water. Energy supply failures can also affect transportation operations, and even after electricity is restored, a significant time lag can occur until transportation services such as subway signals and traffic lights return to operation.[290] Understanding and coping with these interdependencies require cross-sector analysis and engagement by the private sector and within and across different levels of government. As a result, the connection between climate impacts, adaptation, and sustained economic development of cities is a major concern in the region.

The large number of manufacturing, distribution, and storage facilities, as well as historic structures, in the region are also vulnerable to climate shifts and extremes. For example, power plants in New York City tend to be located along the coastline for easy access to water for cooling and maritime-delivered fuel and are often located within about 16 feet (5 m) of sea level.[59] This is not unusual, as there are many power plants and petroleum storage facilities located along the Northeast coastline.[291]

The historic preservation community has begun to address the issue of climate change.[292,293] Many historic districts in cities and towns, such as Annapolis, Maryland, and Newport, Rhode Island, are at low elevations along the coast and now face the threat of rising sea levels.

Preparedness in Cities and Towns

Projected increases in coastal flooding, heavy precipitation, runoff, and extreme heat would have negative impacts on urban centers with disproportionate effects on at-risk communities. Larger cities, including Boston, MA, Burlington, VT, Hartford, CT, Newark, NJ, Manchester, NH, New York, Philadelphia, PA, Pittsburgh, PA, Portland, ME, Providence, RI, and Washington, DC, have begun to plan for climate change and in some instances have started to implement action, particularly when upgrading aging infrastructure (e.g., NYC Special Initiative for Rebuilding and Resiliency 2013, Climate Ready Boston 2016, City of Philadelphia 2016, City of Pittsburgh 2017[294,295,296,297]). Examples from municipalities of varying sizes are common (e.g., U.S. EPA 2017[33]). These cities seek to maintain the within-city and intercity connectivity that fosters growth, diversity, liveliness of urban neighborhoods, and protection of vulnerable populations, including the elderly, young, and disadvantaged. Further, city leaders hope to avoid forced migration of highly vulnerable populations and the loss of historical and cultural resources. City managers and stakeholders recognize that extreme heat events, sea level rise, and storm surge have the potential to lead to complex disasters and sustained critical infrastructure damage. Specific actions cities are taking focus largely on promoting the resilience of critical infrastructure, enhancing the social resilience of communities (especially of vulnerable populations), promoting ecosystem service hazard mitigation, and developing new indicators and monitoring systems to achieve a better understanding of climate risks and to identify adaptation strategies (see Key Message 5) (see also Ch. 11: Urban). In the Northeast region, Superstorm Sandy illustrated urban coastal flooding risk, and many localities, not just those directly impacted by the storm, have developed increased coastal resilience plans and efforts. New York City has been able to put in place a broad set of efforts in a variety of critical infrastructure sectors, including making the subway more protected from flooding (Figure 18.10).

Subway Air Vent Flood Protection

Figure 18.10: The photo shows a subway air vent with a multiuse raised flood protection grate that was installed as part of the post–Superstorm Sandy coastal resilience efforts on West Broadway in lower Manhattan, New York City. Photo credit: William Solecki.

Many Northeast cities are served by combined sewer systems that collect and treat both storm water and municipal wastewater. During heavy rain events, combined systems can be overwhelmed and release untreated sewage into local bodies of water.[298] Moderate flooding events are expected to become more frequent in most of the Northeast during the 21st century because of more intense precipitation related to climate change.[58,142] Finally, increased precipitation and high streamflows also increase streambed erosion, especially when coupled with wetter soils prior to storm events.[299,300] Erosion at bridges can cause bridge failures,[301] leading to transportation disruption, injuries, and potential fatalities.

The impacts of changes in precipitation and temperature on water supply system behavior in the Northeast are complex. Future potable water supplies are expected to be adequate to meet future demand on average across the Northeast, but the number of watersheds where demand exceeds supply is projected to increase under most climate change scenarios.[302] Studies of specific water systems in the Northeast show mixed results. The New York City reservoir system shows high resilience and reliability under different climate change scenarios.[303] Projected flows in the Potomac River, the primary water supply for the Washington, DC, metropolitan area, are lower in most climate change scenarios, with minor to major impacts on water supply.[304]

Key Message 4

Threats to Human Health

Changing climate threatens the health and well-being of people in the Northeast through more extreme weather, warmer temperatures, degradation of air and water quality, and sea level rise. These environmental changes are expected to lead to health-related impacts and costs, including additional deaths, emergency room visits and hospitalizations, and a lower quality of life. Health impacts are expected to vary by location, age, current health, and other characteristics of individuals and communities.

Health Effects of Extreme Heat

Present-day high temperatures (heat) have been conclusively linked to a higher risk of illness and death, particularly among older adults, pregnant women, and children (Ch 14: Human Health). A number of studies have replicated these findings specifically in the Northeast (see Box 18.3; e.g., Wellenius et al. 2017, Bobb et al. 2014, Hondula et al. 2012[305,306,307]). Ambient temperatures and heat-related health effects can vary significantly over small geographic areas due to local land cover (for example, due to the urban heat island effect; see Key Message 3) (see also Ch. 5: Land Changes, KM 1), topography, and the resilience of individuals and communities.[307,308] For

example, older or sicker individuals and those persons who are without access to air conditioning, living in older homes, socially isolated, or working outdoors are considered particularly vulnerable to the effects of heat.[309,310,311]

Annual average temperature over the contiguous United States has increased by 1.2°F (0.7°C) over the last few decades and by 1.8°F (1.0°C) relative to the beginning of the last century. Recent decades are the warmest in at least the past 1,500 years.[312] Average annual temperatures across the Northeast have increased from less than 1°F (0.6°C) in West Virginia to about 3°F (1.7°C) or more in New England since 1901.[18,19] Although the relative risk of death on very hot days is lower today than it was a few decades ago, heat-related illness and death remain significant public health problems in the Northeast.[20,21,22,23] For example, a study in New York City estimated that in 2013 there were 133 excess deaths due to extreme heat.[24]

Annual average temperature in the contiguous United States is expected to increase by an additional 2.5°F (1.4°C) over the next few decades regardless of future greenhouse gas emissions (Ch 2: Climate).[50] By 2050, average annual temperatures in the Northeast are expected to increase by 4.0°F (2.2°C) under the lower scenario (RCP4.5) and 5.1°F (2.8°C) under the higher scenario (RCP8.5) relative to the near present (1975–2005),[50] with several more days of extreme heat occurring throughout the region each year.

These projected increases in temperature are expected to lead to substantially more premature deaths, hospital admissions, and emergency department visits due to heat across the Northeast.[23,25,26,27,28,29] For example, in the Northeast we can expect approximately 650 more excess deaths per year caused by extreme heat by 2050 under either a lower or higher scenario (RCP4.5 or RCP8.5) and 960 (under RCP4.5) to 2,300 (under RCP8.5) more excess deaths per year by 2090.[29]

The risks associated with present-day and projected future heat can be minimized by reducing greenhouse gas emissions, minimizing exposure through urban design, or increasing individual and community resilience.[23,29,313] For example, in the Northeast region, Philadelphia and New York City have been leaders in implementing policies and investing in infrastructure aimed at reducing the number of excess deaths from extreme heat.[314] Compared to the higher scenario (RCP8.5), 1,400 premature deaths from extreme temperatures could be avoided in the Northeast each year by 2090 if global greenhouse gas emissions are consistent with the lower scenario (RCP4.5), resulting in $21 billion in annual savings (in 2015 dollars).[29]

Box 18.3: Rising Temperatures and Heat-Related Emergency Room Visits in Rhode Island

Moderate and extreme heat events already pose a health risk today,[305,306,315,316] and climate change could increase this risk. Of note, days of moderate heat occur much more often compared to days of extreme heat, such that days of moderate heat may, in aggregate, be associated with a larger number of adverse health events.[315] Average summertime temperatures are projected to continue to rise through the end of the century, raising concern about the public health impact of climate change across Northeast communities. A nationwide study projected that some of the largest increases in heat-related mortality would occur in the Northeast region, with an additional 50–100 heat-related deaths per year per million people by 2050 and 120–180 additional deaths per million people by 2100 under the mid-high scenario (RCP6.0).[28] Heat health risks seem to be highest at the start of the warm weather each year[317] and among vulnerable populations such as outdoor workers, young children, and the elderly.

Box 18.3: Rising Temperatures and Heat-Related Emergency Room Visits in Rhode Island, *continued*

In the small, coastal northeastern state of Rhode Island (population of about 1 million), maximum daily temperatures in the summer have trended upwards over the last 60 years such that Rhode Islanders experienced about three more weeks of uncomfortably hot weather over 2015–2016 than in the 1950s (Figure 18.11, left panel). A recent study looking at visits to hospital emergency rooms (ERs) found that the risk of heat-related ER visits increased sharply as maximum daily temperatures climbed above 80°F (Figure 18.11, middle panel).[26] The researchers projected that with continued climate change, Rhode Islanders could experience an additional 400 (6.8% more) heat-related ER visits each year by 2050 and up to an additional 1,500 (24.4% more) such visits each year by 2095 under the higher scenario (RCP8.5; Figure 18.11, right panel). Importantly, about 1,000 fewer annual heat-related ER visits are projected for the end of the century under the lower scenario (RCP4.5) compared to the higher scenario (RCP8.5), representing the potential protective benefit of limiting greenhouse gas emissions. Such reductions would also lead to improvements in air pollution and health starting today.[318,319]

In response to the health threat from heat, local National Weather Service offices issue heat advisories and excessive heat warnings when the forecast calls for very hot weather. Based on the results of a study across multiple states,[305] the National Weather Service Northeast Region updated its heat advisory guidelines to be issued when the heat index is forecast to exceed 95°F for any amount of time on two or more days or 100°F for any amount of time on a single day. Many communities in the Northeast have implemented plans to respond to these heat alerts to better protect the public's health (for example, with the Centers for Disease Control and Prevention's Building Resilience Against Climate Effects program), although gaps in knowledge remain.[34,314] Uncertainties exist in the estimation of the cumulative impact on health of multiple aspects of weather, including heat, drought,[320] and heavy precipitation,[321,322,323] all of which have potential adverse impacts on human health.

Observed and Projected Impacts of Excess Heat on Emergency Room Visits in Rhode Island

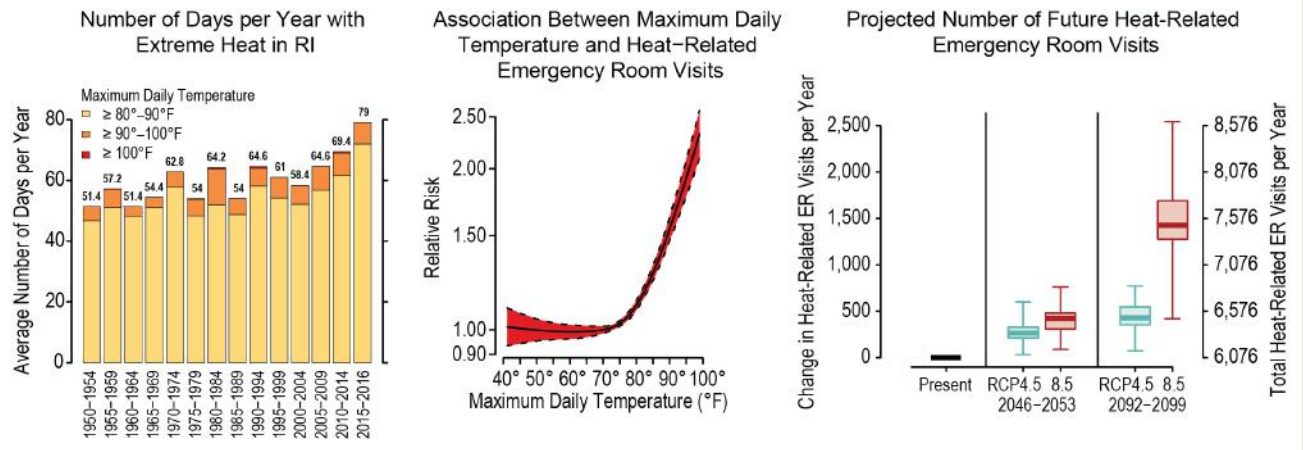


Figure 18.11: This figure shows the observed and projected impacts of excess heat on emergency room visits in Rhode Island. (left) In Rhode Island, maximum daily temperatures in the summer have trended upwards over the last 60 years, such that residents experienced about three more weeks of health-threatening hot weather over 2015–2016 than in the 1950s. (middle) A recent study looking at visits to hospital emergency rooms (ERs) found that the incidence rate of heat-related ER visits rose sharply as maximum daily temperatures climbed above 80°F. (right) The study estimates that with continued climate change, Rhode Islanders could experience an additional 400 (6.8% more) heat-related ER visits each year by 2050 and up to an additional 1,500 (24.4% more) such visits each year by 2095 under the higher scenario (RCP8.5). About 1,000 fewer annual heat-related ER visits are projected for the end of the century under the lower scenario (RCP4.5) compared to the higher scenario (RCP8.5), reflecting the estimated health benefits of adhering to a lower greenhouse gas emissions scenario. Sources: (left) Brown University; (middle, right) adapted from Kingsley et al. 2016.[26] Reproduced from Environmental Health Perspectives.

Health Effects of Air Pollution, Aeroallergens, and Wildfires

Climate change is increasing the risk of illness and death due to higher concentrations of air pollutants in many parts of the United States (Ch. 13: Air Quality). In the Northeast, climate change threatens to reverse improvements in air quality that have been achieved over the past couple of decades. For example, climate change is projected to influence future levels of ground-level ozone pollution in the Northeast by altering weather conditions and impacting emissions from human and natural sources.[324,325,326] This "climate penalty," whereby reductions in ozone precursor emissions are at least partially offset by a changing climate, is projected to lead to substantially more ozone pollution-related deaths;[324,325,327] 200–300 more excess deaths per year by 2050 compared to 2000 by one estimate.[325]

Excess deaths due to ground-level ozone pollution are projected to increase substantially under both lower (RCP4.5) and higher (RCP8.5) scenarios.[327] Reducing global emissions of greenhouse gases from a higher scenario to a lower scenario could prevent approximately 360 deaths per year due to air quality in 2090, saving approximately $5.3 billion per year (in 2015 dollars, undiscounted).[327] Moreover, many sources of the greenhouse gas emissions that contribute to climate change also contribute to degraded air quality today, with adverse effects on people's health. The adverse health risks from air pollution can be reduced in the present and in the future by addressing these common emission sources.[319]

More frequent and severe wildfires due to climate change pose an increasing risk to human health through impacts on air quality (Ch. 13: Air Quality, KM 2). Wildfire smoke can travel hundreds of miles, as occurred in 2015 when Canadian wildfire smoke caused air quality exceedance days in Baltimore, Maryland.[328]

Climate change is also expected to lengthen and intensify pollen seasons in parts of the United States, potentially leading to additional cases of allergic rhinitis (also known as hay fever) and allergic asthma episodes (Ch. 13: Air Quality, KM 3).[29,329] Among individuals with allergic asthma, exposure to certain types of pollen can result in worsening of symptoms leading to increases in allergy medication sales and emergency room visits for asthma, as already documented in New York City.[330]

Indoors, climate change is expected to bring conditions that foster mold growth, such as more dampness, and more frequent power outages that impair ventilation. Damp indoor conditions and mold are both known to be associated with respiratory illnesses including asthma symptoms and wheezing.[331] When damp conditions occur in buildings, rapid action could be warranted—remediation in a northeastern office building after the development of respiratory or severe non-respiratory symptoms by building inhabitants was not effective in reducing symptoms.[332]

Changing Ecosystems and Risk of Vector-Borne Disease

The risk posed by vector-borne diseases (those transmitted by disease-carriers such as fleas, ticks, and mosquitoes) such as Lyme disease and West Nile virus under a changing climate is also of concern in the Northeast region. These diseases, specifically tick-related Lyme disease, have been linked to climate, particularly with abundant late-spring and early-summer moisture. By 2065–2080, under the higher scenario (RCP8.5) it is projected that the period of elevated risk of Lyme disease transmission in the Northeast will begin 0.9–2.8 weeks earlier between Maine and Pennsylvania, compared to the climate observed over 1992–2007).[67] Similarly, a recent analysis estimates that there would be an additional 490 cases of West Nile neuroinvasive disease per year in the Northeast by 2090 under the higher

scenario (RCP8.5) versus 210 additional cases per year under the lower scenario (RCP4.5).[29] The geographic range of suitable habitats for other mosquito vectors such as the northern house mosquito (*Culex pipiens* and *Culex restuans*, which transmit West Nile virus) and the Asian tiger mosquito (*Aedes albopictus*, which can also transmit West Nile virus and other mosquito-borne diseases) is expected to continue shifting northward into New England in the next several decades and through the end of the century as a result of climate change.[333,334]

Gastrointestinal Illness from Waterborne and Foodborne Contaminants

Another consequence of climate change is the spread of marine toxins and pathogens (Key Message 2). Some of these pathogens pose health risks through consumption of contaminated seafood. Harmful algal blooms, which can cause paralytic shellfish poisoning in humans, have become more frequent and longer lasting in the Gulf of Maine.[335] Similarly, pathogenic strains of the waterborne bacteria *Vibrio*—which are already causing thousands of foodborne illnesses per year—have expanded northward and have been responsible for increasing cases of illness in oyster consumers in the Northeast region.[336,337,338]

Combined sewer systems (where municipal wastewater and storm water use the same pipes) are particularly common in the Northeast given the older infrastructure typical of the region.[339] When runoff from heavy precipitation exceeds the capacity of these systems, combined sewer overflow containing untreated sewage is released into local waterways, potentially impacting the quality of water used for recreation or drinking. For example, a study in Massachusetts found an increased risk of gastrointestinal illness with heavy precipitation causing combined sewer overflows.[322] Increased risk of campylobacteriosis and salmonella has been documented in Maryland with increased heavy precipitation and streamflows.[340,341] Moderate flooding events are expected to become more frequent in most of the Northeast during the 21st century because of more intense precipitation related to climate change.[105,142] This could, therefore, increase the frequency of combined sewer overflows and waterborne disease. Some cities and towns are making substantial investments to reduce or eliminate the risks of combined sewer overflows (Figure 18.12).

Storm-related power outages can also pose a risk of foodborne illness.[343] Increased diarrheal illnesses from consumption of spoiled food have also been documented in New York City in 2003 following a power outage that affected millions in the Northeast (Ch. 17: Complex Systems, Box 17.5).[344]

District of Columbia Water and Sewer Authority's Clean Rivers Project

Figure 18.12: The District of Columbia Water and Sewer Authority's Clean Rivers Project[342] aims to reduce combined sewer overflows into area waterways. The Clean Rivers Project is expected to reduce overflows annually by 96% throughout the system and by 98% for the Anacostia River. In addition, the project is expected to reduce the chance of flooding in the areas it serves from approximately 50% to 7% in any given year and reduce nitrogen discharged to the Chesapeake Bay by approximately 1 million pounds per year. Photo credit: Daniel Lobo (CC BY 2.0).

Box 18.4: Role of Public Health and Healthcare Sector in Resilience and Prevention

There are numerous examples of how the public health and healthcare sectors are preparing for climate change and making energy saving changes, as highlighted in the U.S. Department of Health and Human Services' report on enhancing healthcare resilience.[345] One such example occurred in Greenwich, Connecticut, where Greenwich Hospital installed a combined heat and power system that conserves energy and provided stability in the wake of Superstorm Sandy.[346]

In June 2016, severe flooding in West Virginia resulted from a "thousand-year storm"[347] and highlighted the important role of the healthcare sector in building resilience to extreme precipitation events. A recent study of the event described the role of state and federal government working in partnership with healthcare volunteer organizations to effectively mobilize a response in the setting of such a disaster.[348] It emphasized the critical importance of healthcare professionals in providing emotional and mental health support to the response volunteers and the affected communities, as well as a need to increase capacity in these areas.[348] See Key Message 5 in this chapter and Chapter 14: Human Health, Key Message 3 for more information on additional adaptation efforts that protect health.

Figure 18.13: A Red Cross volunteer talks with a community resident after the 2016 West Virginia floods. Additionally, local medical professionals mobilized to staff temporary clinical sites. Photo credit: National Guard Bureau Public Affairs.

Mental Health and Well-Being

In addition to the adverse impacts on people's physical health, climate change is also associated with adverse impacts on mental health (Ch. 14: Human Health, KM 1). Specifically in the Northeast region, sea level rise, storm surge, and extreme precipitation events associated with climate change will contribute to higher risk of flooding in both coastal and inland areas—particularly in urban areas with large amounts of impervious surface that increases water runoff. In addition to the risks of physical injury, waterborne disease, and healthcare service disruption caused by flooding, lasting mental health consequences, such as anxiety, depression, and post-traumatic stress disorder can impact affected communities, as was observed in the wake of Superstorm Sandy in 2012 (Box 18.4).[349] Extreme weather events can have both immediate, short-term effects, as well as longer-term impacts on mental health and well-being that can last years after the specific event.

Extreme heat can also affect mental health and well-being. Higher outdoor temperatures are associated with decreases in subtle aspects of well-being such as decreased joy and happiness[350] and increased aggression and violence.[351] Underlying mental health conditions and geography also affect vulnerability. For example, a study of hospitalization for heat-related illness among people with mental health disorders showed increased risk in rural versus urban areas, possibly due to lower availability of mental health services in these rural areas.[352]

Separately, large population changes from climate-driven human migration could substantially influence both coastal and inland communities in the Northeast region (see also Key Messages 2 and 5).[285] The impacts of human migration on health and well-being depend on myriad factors, including the context of the migration.[353]

Regional Variation in Health Impacts and Vulnerability

Although climate change affects all residents of the Northeast region, risks are not experienced equally. The impact of climate change on an individual depends on the degree of exposure, the individual sensitivity to that exposure, and the individual or community-level capacity to recover (Ch. 14: Human Health, KM 2).[354] Thus, health impacts of climate change will vary across people and communities of the Northeast region depending on social, socioeconomic, demographic, and societal factors; community adaptation efforts; and underlying individual vulnerability (see Key Message 5) (see also Ch. 28: Adaptation). Particularly vulnerable groups include older or socially isolated adults, children, low-income communities, and communities of color.

Key Message 5

Adaptation to Climate Change Is Underway

Communities in the Northeast are proactively planning and implementing actions to reduce risks posed by climate change. Using decision support tools to develop and apply adaptation strategies informs both the value of adopting solutions and the remaining challenges. Experience since the last assessment provides a foundation to advance future adaptation efforts.

Communities, towns, cities, counties, states, and tribes across the Northeast are engaged in efforts to build resilience to environmental challenges and adapt to a changing climate. Developing and implementing climate adaptation strategies in daily practice often occur in collaboration with state and federal agencies (e.g., New Jersey Climate Adaptation Alliance, New York Climate Clearinghouse, Massachusetts StormSmart Coasts and Climate Action Tool, Rhode Island StormTools, EPA, CDC).[30,31,32,33,34,355,356] Advances in rural towns, cities, and suburban areas include low-cost adjustments of existing building codes and standards. In coastal areas, partnerships among local communities and federal and state agencies leverage federal adaptation tools and decision support frameworks (the National Oceanic and Atmospheric Administration's [NOAA] Digital Coast, the U.S. Geological Survey's [USGS] Coastal Change Hazards Portal, New Jersey's Getting to Resilience).

Increasingly, cities and towns across the Northeast region are developing or implementing plans for adaptation and resilience in the face of a changing climate (e.g., EPA 2017[33]). These approaches are designed to maintain and enhance the everyday life of residents and promote economic development. In some cities, adaptation planning has been used to respond to present and future challenges in the built environment. Regional efforts have recommended changes in design standards when building, replacing, or retrofitting infrastructure to account for a changing climate (Box 18.5). For example, the Port Authority of New York and New Jersey provided guidelines for engineers to account for projected changes in temperature, precipitation, and sea level rise when designing infrastructure assets.[357] The cities of Philadelphia, Pennsylvania,[296] Utica, New York,[358] and Boston, Massachusetts,[295] promote the use of green infrastructure to build resilience, particularly in response to flooding risk (Ch. 8: Coastal, Figure 8.2). In Jamaica Bay, New York, post–Superstorm Sandy efforts have fostered a set of local, regional, state, and federal actions that link resilience efforts to current climate risk, along with the potential for accelerated sea level rise and its implications for increased flood frequency (Ch. 28: Adaptation, KM 1).[359]

The issue of water security has emerged from vulnerability assessments and cuts across urban and rural communities. One example is the Washington, DC, metropolitan area's potential use of the Potomac and Occoquan estuaries as water supplies and of retired quarries as water storage facilities.[304] Adaptive reservoir operations have been implemented in the Northeast and other regions of the United States to better manage plausible future climate conditions and to meet other management goals (Ch. 3: Water, KM 3). Tribal nations have also focused on adaptation and the vulnerability of their water supplies, based on long-standing local values and traditional knowledge, including the use of water for drinking, habitat for fish and wildlife, agriculture, and cultural purposes.[97,360,361]

While resilience efforts have focused on microscale adaptations to current climate risks, communities are increasingly seeing a need for larger-scale adaptation efforts. Wide disparities in adaptive capacity exist among communities in the region. Larger, often better-resourced communities have created climate offices and programs, while response has lagged in smaller or poorer communities that are often more dependent on county- or state-level programs and expertise. The move from small-scale to larger-scale and more transformative adaptation efforts involves complex policy transition planning, social and economic development, and equity considerations (Ch. 28: Adaptation, KM 4).[362,363] This includes attention to community concerns about green gentrification—the practice of making environmental improvements in urban areas—that generally increases property values but often also drives out lower-income residents.[364]

Box 18.5: Adapting the Northeast's Cultural Heritage

A defining characteristic of the Northeast region is its rich, dense record of cultural heritage, marked by historic structures, archaeological sites, and cultural landscapes. The ability to preserve this cultural heritage is challenged by climate change. National parks and historic sites in the Northeast are already witnessing cultural resource impacts from climate change, and more impacts are expected in the future.[236] These cultural resources present unique adaptation challenges, and the region is moving forward with planning for future adaptation.

Superstorm Sandy caused substantial damage to coastal New York Harbor parks, including Gateway National Recreation Area and Statue of Liberty National Monument, where buildings and the landscape surrounding the statue and on Ellis Island were impacted and the museum collections were threatened by the loss of climate control systems that were flooded.[370,371] Sea level rise amplifies the impacts of storm events such as Superstorm Sandy, and the parks are using recovery as an opportunity to rebuild with more resilience to future storms.[371,372,373] Heating and electrical systems in historic buildings have been elevated from basement levels. Design changes, such as using non-mold-growing materials and other engineering solutions, have been made while maintaining the buildings' historic character. Following the storm, Gateway National Recreation Area added climate change vulnerability to their planning process for prioritizing historic structures between preserve, stabilize, or ruin. The recreation area has been implementing these priorities as part of the recovery process, providing examples of climate adaptation implementation.[359,374] The human community on Rockaways peninsula also responded to Sandy by using urban forestry and agricultural practices to recover and to buffer against the impact of future storms (see Building Resiliency at the Rockaways 360 tour[375]).

Decision Support Tools and Adaptation Actions

While adaptation is progressing in a variety of forms in the Northeast region, many efforts have focused on assessing risks and developing decision support tools. Many of these assessments and tools have proven useful for specific purposes. Structured decision-making is where decision-makers engage at the outset to define a problem, objectives, alternative management actions, and the consequences and tradeoffs of such actions—before making any decisions. It is being increasingly applied to design management plans, determine research needs, and allocate resources to preserve habitat and resources throughout the region.[151,365,366,367] There has been little attention devoted to evaluating and communicating the suitability and robustness of the many tools that are now available. Efforts to evaluate decision support tools and processes in a rigorous scientific manner would help stakeholders choose the best tools to answer particular questions under specific circumstances.

One significant advancement that communities and infrastructure managers have made in recent years has been the development of risk, impact, and adaptation indicators, as well as monitoring systems to measure and understand climate change and its impacts.[15] In recognizing the economic impacts of infrastructure service loss and disruption, government agencies have begun adaptation analyses to identify those infrastructure elements most critical for regional economic resilience during climate-related disruptions, as well as to identify communities most exposed to acute and chronic climate risks.[45,368,369]

Resource managers, community leaders, and other stakeholders are altering the management of coastal areas and resources in the context of climate change (Boxes 18.6 and 18.7).

Box 18.6: Building Resilience in the Chesapeake Bay Watershed

The Chesapeake Bay watershed is experiencing stronger and more frequent storms, an increase in heavy precipitation events, increasing bay water temperatures, and a rise in sea level. These trends vary throughout the watershed and over time but are expected to continue over the next century under all scenarios considered. The trends are altering both the ecosystems and mainland and island communities of the Chesapeake Bay watershed. Achieving watershed goals would require changes in policies, programs, and/or projects to achieve restoration, sustainability, conservation, and protection goals for the entire system.

To gain a better understanding of the likely impacts of climate change, as well as potential management solutions for the watershed, the 2014 Chesapeake Bay Watershed Agreement committed the NOAA Chesapeake Bay Program (CBP) Partnership to take action to "increase the resiliency of the Chesapeake Bay watershed, including its living resources, habitats, public infrastructure and communities, to withstand adverse impacts from changing environmental and climate conditions." This new Bay Agreement goal builds on the 2010 Total Maximum Daily Load (TMDL) documentation and 2009 Presidential Executive Order 13508[376,377] that called for an assessment of the impacts of a changing climate on the Chesapeake Bay's water quality and living resources. To achieve this goal and regulatory mandates, the CBP Partnership is undertaking efforts to monitor and assess trends and likely impacts of changing climatic and sea level conditions on the Chesapeake Bay ecosystem and to pursue, design, and construct restoration and protection projects to enhance resilience. The CBP Climate

Box 18.6: Building Resilience in the Chesapeake Bay Watershed, *continued*

Resiliency Workgroup's Management Strategy recognizes that it is important to build community and institutional capacity and to develop analytical capability to build cross-science disciplinary knowledge and better understanding of societal responses. A significant activity now underway is geared towards the midpoint assessment of progress towards the 2025 Chesapeake Bay TMDL goal for water quality standard attainment. As part of the TMDL midpoint assessment, the CBP Partnership has developed tools and procedures to quantify the effects of climate change on watershed flows and pollutant loads, storm intensity, increased estuarine temperatures, sea level rise, and ecosystem influences, including loss of tidal wetland attenuation with sea level rise. Current modeling efforts are underway to assess potential climate change impacts under a range of projected climate change outcomes for 2025 and 2050.[378]

Addressing climate change within the context of established watershed planning and regulatory efforts is extremely complex and requires sound climate science, climate assessments, modeling, policy development, and stakeholder engagement (Ch. 28: Adaptation, Figure 28.1). The CBP Partnership is tackling this challenge on all of these fronts, with priority directed to understanding what is needed to achieve the 2025 nutrient reduction goals and the best management practices required to achieve climate-resilient rehabilitation goals.

For example, research in Delaware is exploring the use of seashore mallow as a transitional salt-tolerant crop because of gradual wetland migration onto agricultural lands as sea levels rise.[379] Commercial and recreational fisheries and tourism depend upon living marine resources. Climate adaptation in ocean fisheries will entail coping and long-term planning responses at multiple levels of communities, industry, and management systems.[380] Fishers have traditionally switched species as needed based on ecosystem or market conditions; this will continue to be an important adaptation option, but it is increasingly constrained by regulatory approaches in fisheries.[155,178,179,202] Longer-term planning for climate adaptation has included state commissions to evaluate ocean acidification threats,[381,382] federal efforts to articulate science strategies,[383,384,385] species vulnerability assessments,[143,186] coupled social–ecological vulnerability assessments for fishing communities,[45] and planning for the potential inland migration of coastal populations due to sea level rise.[386]

The winter recreation industry has long considered snowmaking an adaptation to climate change.[387] Snowmaking improvements should assist with the viability of some Northeast ski areas,[117] while new tourism opportunities emerge.[388]

In order to sustain and advance these and other planned efforts towards climate change adaptation and resilience, decision-makers in the Northeast need to be aware of existing constraints and emerging issues. Constraints from the management, economic, and social context are highly uncertain.[389] These efforts have faced a variety of barriers and limitations, including lack of funding and jurisdictional and legal constraints.[390,391] In many cases, adaptation has been limited to coping responses that address short-term needs and are feasible within the current institutional context, whereas longer-term, more transformative efforts will likely require complex policy transition planning and frameworks that can address social and economic equality.[363] The need for solutions that support industry and community flexibility in responding to climate-related changes has also been recognized.[45,178]

Earth's changing climate is one of several stressors on human and natural systems, and it can work to exacerbate existing vulnerabilities and inequalities. Implementing resilience planning and climate change adaptation in

Box 18.7: Science for Balancing Wildlife and Human Needs in the Face of Sea Level Rise

Policymakers, agencies, and natural resource managers are under increasing pressure to manage coastal areas to meet social, economic, and natural resource demands, particularly as sea levels rise. Scientific knowledge of coastal processes and habitat use can support decision-makers as they balance these often-conflicting human and ecological needs. In collaboration with a wide network of natural resource professionals from state and federal agencies (including the U.S. Fish and Wildlife Service and National Park Service) and private conservation organizations, a research team from the U.S. Geological Survey (USGS) is conducting research and developing tools to identify suitable coastal habitats for species of concern, such as the piping plover (*Charadrius melodus*)—an ecologically important species with low population numbers—under a variety of sea level rise scenarios.

The multidisciplinary USGS team uses historical and current habitat availability and coastal characteristics to develop models that forecast likely future habitat from Maine to North Carolina.[392,393] The collaborative partners, both researchers and managers, are critical to the program: they aid in data collection efforts through the "iPlover" smartphone application[394] and help scientists focus research on specific management questions. Because these shorebirds favor sandy beaches that overwash frequently during storms, the resulting habitat maps also define current and future areas of high hazard exposure for humans and infrastructure.

Figure 18.14: (a, b) These photographs show suitable piping plover habitat for (c) rearing chicks along the U.S. Atlantic coast. Photo credits: (a, b) Sara Zeigler, U.S. Geological Survey; (c) Josh Seibel, U.S. Fish and Wildlife Service.

Land-use planners can use results to determine optimal locations for constructing recreational facilities that minimize impacts on sensitive habitats and have a low probability of being overwashed. Alternatively, results can help resource managers proactively protect the highest-quality habitats to meet near- and long-term conservation goals and, in so doing, increase beach access for users by reducing human–bird conflicts and improving the certainty of beach availability for recreational use.

order to preserve the cultural, economic, and natural heritage of the Northeast would require ongoing collaboration among tribal, rural, and urban communities as well as municipal, state, tribal, and federal agencies. The number and scope of existing adaptation plans in the Northeast show that many people in the region consider this heritage to be important.

Acknowledgments

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Traceable Accounts

Process Description

It is understood that authors for a regional assessment must have scientific and regional credibility in the topical areas. Each author must also be willing and interested in serving in this capacity. Author selection for the Northeast chapter proceeded as follows:

First, the U.S. Global Change Research Program (USGCRP) released a Call for Public Nominations. Interested scientists were either nominated or self-nominated and their names placed into a database. The concurrent USGCRP Call for Public Nominations also solicited scientists to serve as chapter leads. Both lists were reviewed by the USGCRP with input from the coordinating lead author (CLA) and from the National Climate Assessment (NCA) Steering Committee. All regional chapter lead (CL) authors were selected by the USGCRP at the same time. The CLA and CL then convened to review the author nominations list as a "first cut" in identifying potential chapter authors for this chapter. Using their knowledge of the Northeast's landscape and challenges, the CLA and CL used the list of national chapter topics that would be most relevant for the region. That topical list was associated with scientific expertise and a subset of the author list.

In the second phase, the CLA and CL used both the list of nominees as well as other scientists from around the region to build an author team that was representative of the Northeast's geography, institutional affiliation (federal agencies and academic and research institutions), depth of subject matter expertise, and knowledge of selected regional topics. Eleven authors were thus identified by December 2016, and the twelfth author was invited in April 2017 to better represent tribal knowledge in the chapter.

Lastly, the authors were contacted by the CL to determine their level of interest and willingness to serve as experts on the region's topics of water resources, agriculture and natural resources, oceans and marine ecosystems, coastal issues, health, and the built environment and urban issues.

On the due diligence of determining the region's topical areas of focus

The first two drafts of the Northeast chapter were structured around the themes of water resources, agriculture and natural resources, oceans and marine ecosystems, coastal issues, health, and the built environment and urban issues. During the USGCRP-sponsored Regional Engagement Workshop held in Boston on February 10, 2017, feedback was solicited from approximately 150 online participants (comprising transportation officials, coastal managers, urban planners, city managers, fisheries managers, forest managers, state officials, and others) around the Northeast and other parts of the United States, on both the content of these topical areas and important focal areas for the region. Additional inputs were solicited from other in-person meetings such as the ICNet workshop and American Association of Geographers meetings, both held in April 2017. All feedback was then compiled with the lessons learned from the USGCRP CLA-CL meeting in Washington, DC, also held in April 2017. On April 28, 2017, the author team met in Burlington, Vermont, and reworked the chapter's structure around the risk-based framing of interest to 1) changing seasonality, 2) coastal/ocean resources, 3) rural communities and livelihoods, 4) urban interconnectedness, and 5) adaptation.

Key Message 1

Changing Seasons Affect Rural Ecosystems, Environments, and Economies

The seasonality of the Northeast is central to the region's sense of place and is an important driver of rural economies. Less distinct seasons with milder winter and earlier spring conditions (*very high confidence*) are already altering ecosystems and environments (*high confidence*) in ways that adversely impact tourism (*very high confidence*), farming (*high confidence*), and forestry (*medium confidence*). The region's rural industries and livelihoods are at risk from further changes to forests, wildlife, snowpack, and streamflow (*likely*).

Description of evidence base

Multiple lines of evidence show that changes in seasonal temperature and precipitation cycles have been observed in the Northeast.[3,4,109,110,124,154,158] Projected increases in winter air temperatures under lower and higher scenarios (RCP4.5 and RCP8.5)[3,4] will result in shorter and milder cold seasons, a longer frost-free season,[3] and decreased regional snow cover and earlier snowmelt.[108,109,110,395,396,397] Observed seasonal changes to streamflows in response to increased winter precipitation, changes in snow hydrology,[112,138,139,140] and an earlier but prolonged transition into spring[68] are projected to continue.[105]

These changes are affecting a number of plant and animal species throughout the region, including earlier bloom times and leaf-out,[71,73,158] spawning,[164] migration,[84,166,398] and insect emergence,[74] as well as longer growing seasons,[72] delayed senescence, and enhanced leaf color change.[103] Milder winters will likely contribute to the range expansion of wildlife and insect species,[399] increase the size of certain herbivore populations[78] and their exposure to parasitism,[81,82] and increase the vulnerability of an array of plant and animal species to change.[66,103,143]

Warmer winters will likely contribute to declining yields for specialty crops[35] and fewer operational days for logging[88] and snow-dependent recreation.[115,116,118] Excess moisture is the leading cause of crop loss in the Northeast,[35] and the observed increase in precipitation amount, intensity, and persistence is projected to continue under both lower and higher scenarios.[3,4,124,125]

Major uncertainties

Warmer fall temperatures affect senescence, fruit ripening, migration, and hibernation, but are less well studied in the region[98] and must be considered alongside other climatic factors such as drought. Projections for summer rainfall in the Northeast are uncertain,[4] but evaporative demand for surface moisture is expected to increase with projected increases in summer temperatures.[3,4] Water use is highest during the warm season;[141,400] how much this will affect water availability for agricultural use depends on the frequency and intensity of drought during the growing season.[302]

Description of confidence and likelihood

There is *high confidence* that the combined effects of increasing winter and early-spring temperatures and increasing winter precipitation (*very high confidence*) are changing aquatic and terrestrial habitats and affecting the species adapted to them. The impact of changing seasonal temperature, moisture conditions, and habitats will vary geographically and impact interactions

among species. It is *likely* that some will not adapt. There is *high confidence* that over the next century, some species will decline while other species introduced to the region thrive as conditions change. There is *high confidence* that increased precipitation in early spring will negatively impact farming, but the response of vegetation to future changes in seasonal temperature and moisture conditions depends on plant hardiness for *medium confidence* in the level of risk to specialty crops and forestry. A reduction in the length of the snow season by mid-century is *highly likely* under lower and higher scenarios, with *very high confidence* that the winter recreation industry will be negatively impacted by the end of the century under lower and higher scenarios (RCP4.5 and RCP8.5).

Key Message 2

Changing Coastal and Ocean Habitats, Ecosystem Services, and Livelihoods

The Northeast's coast and ocean support commerce, tourism, and recreation that are important to the region's economy and way of life. Warmer ocean temperatures, sea level rise, and ocean acidification (*high confidence*) threaten these services (*likely*). The adaptive capacity of marine ecosystems and coastal communities will influence ecological and socioeconomic outcomes as climate risks increase (*high confidence*).

Description of evidence base

Warming rates on the Northeast Shelf have been higher than experienced in other ocean regions,[39] and climate projections indicate that warming in this region will continue to exceed rates expected in other ocean regions.[48,49] Multiple lines of research have shown that changes in ocean temperatures and acidification have resulted in distribution,[7,8,10] productivity,[39,173,191,401] and phenology shifts[155,158,163,164,166] in marine populations. These shifts have impacted marine fisheries and prompted industry adaptations to changes.[155,176,200]

Research also shows that sea level rise has been[12,46,205,206] and will be higher in the Northeast with respect to the rest of the United States[12,249,250,251] due largely to vertical land movement,[207,208,209] varying atmospheric shifts and ocean dynamics,[210,211,212,213,215,252] and ice mass loss from the polar regions.[214] High tide flooding has increased[216,402] and will continue to increase,[403] and storm surges due to stronger and more frequent hurricanes[50,254,255] have been and will be amplified by sea level rise.[217,220,221,289] Climate-related coastal impacts on the landscape include greater potential for coastal flooding, erosion, overwash, barrier island breaching and disaggregation, and marsh conversion to open water,[12,216,223,226,256,257,258,259,263,279,404] which will directly affect the ability of ecosystems to sustain many of the services they provide. Changes to salt marshes in response to sea level rise have already been observed in some coastal settings in the region, although their impacts are site specific and variable.[265,266,267,268,269,270,271,405] Studies quantifying sea level rise impacts on other types of coastal settings (such as beaches) in the region are more limited; however, there is consensus on what impacts under higher rates of relative sea level rise might look like due to geologic history and modern analogs elsewhere (such as the Louisiana coast).[12,226,404] Although probabilistically low, worst-case sea level rise projections that account for ice sheet collapse[47,406] would result in sea level rise rates far beyond the rates at which natural systems are likely able to adapt,[274,275,280] affecting not only ecosystems function and services but also likely substantially changing the coastal landscape largely through inundation.[223]

Major uncertainties

Although work to value coastal and marine ecosystems services is still evolving,[6,41,281] changes to coastal ecosystem services will depend largely on the adaptability of the coastal landscape, direct hits from storms, and rate of sea level rise, which have identified uncertainties. Lower sea level rise rates are more probable, though the timing of ice sheet collapse[407] and the variability of ocean dynamics are still not well understood[210,211,215] and will dramatically affect the rate of rise.[47,406] It is also difficult to anticipate how humans will contend with changes along the coast[389] and how adjacent natural settings will respond. Furthermore, specific tipping points for many coastal ecosystems are still not well resolved[275,277,280] and vary due to site-specific conditions[224,274]

The Northeast Shelf is sensitive to ocean acidification, and many fisheries in the region are dependent on shell-forming organisms.[181,182,186] However, few studies that have investigated the impacts of ocean acidification on species biology and ecology used native populations from the region[182] or tested the effects at acidification levels expected over the next 20–40 years.[143] Moreover, there are limited studies that consider the effects of climate change in conjunction with multiple other stressors that affect marine populations.[39,40,178,408] Limited understanding of the adaptive capacity of species to environmental changes presents major uncertainties in ecosystem responses to climate change.[143,409] How humans will respond to changes in ecosystems is also not well known, yet these decisions will shape how marine industries and coastal communities are affected by climate change.[45]

Description of confidence and likelihood

Warming ocean temperatures (*high confidence*), acidification (*high confidence*), and sea level rise (*very high confidence*) will alter coastal and ocean ecosystems (*likely*) and threaten the ecosystems services provided by the coasts and oceans (*likely*) in the Northeast. There is *high confidence* that ocean temperatures have caused shifts in the distribution, productivity, and phenology of marine species and *very high confidence* that high tide flooding and storm surge impacts are being amplified by sea level rise. Because much will depend on how humans choose to address or adapt to these problems, and as there is considerable uncertainty over the extent to which many of these coastal systems will be able to adapt, there is *medium confidence* in the level of risk to traditions and livelihoods. It is *likely* that under higher scenarios, sea level rise will significantly alter the coastal landscape, and rising temperatures and acidification will affect marine populations and fisheries.

Key Message 3

Maintaining Urban Areas and Communities and Their Interconnectedness

The Northeast's urban centers and their interconnections are regional and national hubs for cultural and economic activity. Major negative impacts on critical infrastructure, urban economies, and nationally significant historic sites are already occurring and will become more common with a changing climate. (*High Confidence*)

Description of evidence base

The urban built environment and related supply and management systems are at increased risk of disruption from a variety of increasing climate risks. These risks emerge from accelerated sea level rise as well as increased frequency of coastal and estuarine flooding, intense precipitation events, urban heating and heat waves, and drought.

Coastal flooding can lead to adverse health consequences, loss of life, and damaged property and infrastructure.[368] Much of the region's major industries and cities are located along the coast, with 88% of the region's population and 68% of the regional gross domestic product.[260] High tide flooding is also increasingly problematic and costly.[47] Rising sea level and amplified storm events can increase the magnitude and geographic size of a coastal flood event. The frequency of dangerous coastal flooding in the Northeast would more than triple with 2 feet of sea level rise.[93] In Boston, the areal extent of a 1% (1 in 100 chance of occurring in any given year) flood is expected to increase multifold in many coastal neighborhoods.[295] However, there will likely be notable variability across coastal locations. Using the 2014 U.S. National Climate Assessment's Intermediate-High scenario for sea level rise (a global rise of 1.2 meters by 2100), the median number of flood events per year for the Northeast is projected to increase from 1 event per year experienced today to 5 events by 2030 and 25 events by 2045, with significant variation within the region.[410]

Intense precipitation events can lead to riverine and street-level flooding affecting urban environments. Over recent decades, the Northeast has experienced an increase of intense precipitation events, particularly in the spring and fall.[411] From 1958 to 2016, the number of heaviest 1% precipitation events (that is, an event that has a 1% chance of occurring in any given year) in the Northeast has increased by 55%.[58] A recent study suggests that this trend began rather abruptly after 1996, though uniformly across the region.[411]

Urban heating and heat waves threaten the health of the urban population and the integrity of the urban landscape. Due to the urban heat island effect, summer surface temperatures across Northeast cities were an average of 13°F to 16°F (7°C to 9°C) warmer than surrounding rural areas over a three-year period, 2003 to 2005.[412] This is of concern, as rising temperatures increase heat- and pollution-related mortality while also stressing energy demands across the urban environment.[413] However, the degree of urban heat island intensity varies across cities depending on local factors such as whether the city is coastal or inland.[414] Recent analysis of mortality in major cities of the Northeast suggests that the region could experience an additional 2,300 deaths per year by 2090 from extreme heat under RCP8.5 (compared to an estimated 970 deaths per year under the lower scenario, RCP4.5) compared to 1989–2000.[29] Another study that considered 1,692 cities around the world suggested that without mitigation, total economic costs associated with climate change could be 2.6 times higher due to the warmer temperatures in urban versus extra-urban environments.[415]

Changes in temperature and precipitation can have dramatic impacts on urban water supply available for municipal and industrial uses. Under a higher scenario (RCP8.5), the Northeast is projected to experience cumulative losses of $730 million (discounted at 3% in 2015 dollars) due to water supply shortfalls for the period 2015 to 2099.[29] Under a lower scenario (RCP4.5), the Northeast is projected to sustain losses of $510 million (discounted at 3% in 2015 dollars).[29] The losses are largely projected for the more southern and coastal areas in the region.

Major uncertainties

Projecting changes in urban pollution and air quality under a changing climate is challenging given the associated complex chemistry and underlying factors that influence it. For example, fine particulates ($PM_{2.5}$; that is, particles with a diameter of or less than 2.5 micrometers) are affected by cloud processes and precipitation, amongst other meteorological processes, leading to considerable uncertainty in the geographic distribution and overall trend in both modeling analysis and the literature.[29] Land use can also play an unexpected role, such as planting trees as a mitigation option that may lead to increases in volatile organic compounds (VOCs), which, in a VOC-limited environment that can exist in some urban areas such as New York City, may increase ozone concentrations (however, it is noted that most of the Northeast region is limited by the availability of nitrogen oxides).[327]

Interdependencies among infrastructure sectors can lead to unexpected and amplified consequences in response to extreme weather events. However, it is unclear how society may choose to invest in the built environment, possibly strengthening urban infrastructure to plausible future conditions.

Description of confidence and likelihood

There is *high confidence* that weather-related impacts on urban centers already experienced today will become more common under a changing climate. For the Northeast, sea level rise is projected to occur at a faster rate than the global average, potentially increasing the impact of moderate and severe coastal flooding.[47]

By the end of the century and under a higher scenario (RCP8.5), Coupled Model Intercomparison Project Phase 5 (CMIP5) models suggest that annual average temperatures will increase by more than 9°F (16°C) for much of the region (2071–2100 compared to 1976–2005), while precipitation is projected to increase, particularly during winter and spring.[50]

Extreme events that impact urban environments have been observed to increase over much of the United States and are projected to continue to intensify. There is *high confidence* that heavy precipitation events have increased in intensity and frequency since 1901, with the largest increase in the Northeast, a trend projected to continue.[50] There is *very high confidence* that extreme heat events are increasing across most regions worldwide, a trend very likely to continue.[50] Extreme precipitation from tropical cyclones has not demonstrated a clear observed trend but is expected to increase in the future.[50,253] Research has suggested that the number of tropical cyclones will overall increase with future warming.[416] However, this finding is contradicted by results using a high-resolution dynamical downscaling study under a lower scenario (RCP4.5), which suggests overall reduction in frequency of tropical cyclones but an increase in the occurrence of storms of Saffir–Simpson categories 4 and 5.[50]

Key Message 4

Threats to Human Health

Changing climate threatens the health and well-being of people in the Northeast through more extreme weather, warmer temperatures, degradation of air and water quality, and sea level rise (*very high confidence*). These environmental changes are expected to lead to health-related impacts and costs, including additional deaths, emergency room visits and hospitalizations, and a lower quality of life (*very high confidence*). Health impacts are expected to vary by location, age, current health, and other characteristics of individuals and communities (*very high confidence*).

Description of evidence base

Extreme storms and temperatures, overall warmer temperatures, degradation of air and water quality, and sea level rise are all associated with adverse health outcomes from heat,[20,21,22,23,305,306,307] poor air quality,[324,325,326] disease-transmitting vectors,[67,333,334] contaminated food and water,[322,340,341,344] harmful algal blooms,[335] and traumatic stress or health service disruption.[17,349] The underlying susceptibility of populations determines whether or not there are health impacts from an exposure and the severity of such impacts.[307,308]

Major uncertainties

Uncertainty remains in projections of the magnitude of future changes in particulate matter, humidity, and wildfires and how these changes may influence health risks. For example, health effects of future extreme heat may be exacerbated by future changes in absolute or relative humidity.

Health impacts are ultimately determined by not just the environmental hazard but also the amount of exposure, size and underlying susceptibility of the exposed population, and other factors such as health insurance coverage and access to timely healthcare services. In projecting future health risks, researchers acknowledge these challenges and use different analytic approaches to address this uncertainty or note it as a limitation.[23,28,326]

In addition, there is a paucity of literature that considers the joint or cumulative impacts on health of multiple climatic hazards. Additional areas where the literature base is limited include specific health impacts related to different types of climate-related migration, the impact of climatic factors on mental health, and the specific timing and geographic range of shifting disease-carrying vectors.

Description of confidence and likelihood

There is *very high confidence* that extreme weather, warmer temperatures, degradation of air and water quality, and sea level rise threaten the health and well-being of people in the Northeast. There is *very high confidence* that these climate-related environmental changes will lead to additional adverse health-related impacts and costs, including premature deaths, more emergency department visits and hospitalizations, and lower quality of life. There is *very high confidence* that climate-related health impacts will vary by location, age, current health, and other characteristics of individuals and communities.

Key Message 5

Adaptation to Climate Change Is Underway

Communities in the Northeast are proactively planning (*high confidence*) and implementing (*medium confidence*) actions to reduce risks posed by climate change. Using decision support tools to develop and apply adaptation strategies informs both the value of adopting solutions and the remaining challenges (*high confidence*). Experience since the last assessment provides a foundation to advance future adaptation efforts (*high confidence*).

Description of evidence base

Reports on climate adaptation and resilience planning have been published by city, state, and tribal governments and by regional and federal agencies in the Northeast. Examples include the Interstate Commission on the Potomac River Basin (for the Washington, DC, metropolitan area),[304] Boston,[295] the Port Authority of New York and New Jersey,[357] the St. Regis Mohawk Tribe,[360] the U.S. Army Corps of Engineers,[368] the State of Maine,[381] and southeastern Connecticut.[417] Structured decision-making is being applied to design management plans, determine research needs, and allocate resources[365] to preserve habitat and resources throughout the region.[151,366,367]

Major uncertainties

The percentage of communities in the Northeast that are planning for climate adaptation and resilience and the percentage of those using decision support tools are not known. More case studies would be needed to evaluate the effectiveness of adaptation actions.

Description of confidence and likelihood

There is *high confidence* that there are communities in the Northeast undertaking planning efforts to reduce risks posed from climate change and *medium confidence* that they are implementing climate adaptation. There is *high confidence* that decision support tools are informative and *medium confidence* that these communities are using decision support tools to find solutions for adaptation that are workable. There is *high confidence* that early adoption is occurring in some communities and that this provides a foundation for future efforts. This Key Message does not address trends into the future, and therefore likelihood is not applicable.

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19 Southeast

Red mangrove in Titusville, Florida

Key Message 1

Urban Infrastructure and Health Risks

Many southeastern cities are particularly vulnerable to climate change compared to cities in other regions, with expected impacts to infrastructure and human health. The vibrancy and viability of these metropolitan areas, including the people and critical regional resources located in them, are increasingly at risk due to heat, flooding, and vector-borne disease brought about by a changing climate. Many of these urban areas are rapidly growing and offer opportunities to adopt effective adaptation efforts to prevent future negative impacts of climate change.

Key Message 2

Increasing Flood Risks in Coastal and Low-Lying Regions

The Southeast's coastal plain and inland low-lying regions support a rapidly growing population, a tourism economy, critical industries, and important cultural resources that are highly vulnerable to climate change impacts. The combined effects of changing extreme rainfall events and sea level rise are already increasing flood frequencies, which impacts property values and infrastructure viability, particularly in coastal cities. Without significant adaptation measures, these regions are projected to experience daily high tide flooding by the end of the century.

Key Message 3

Natural Ecosystems Will Be Transformed

The Southeast's diverse natural systems, which provide many benefits to society, will be transformed by climate change. Changing winter temperature extremes, wildfire patterns, sea levels, hurricanes, floods, droughts, and warming ocean temperatures are expected to redistribute species and greatly modify ecosystems. As a result, the ecological resources that people depend on for livelihood, protection, and well-being are increasingly at risk, and future generations can expect to experience and interact with natural systems that are much different than those that we see today.

Key Message 4

Economic and Health Risks for Rural Communities

Rural communities are integral to the Southeast's cultural heritage and to the strong agricultural and forest products industries across the region. More frequent extreme heat episodes and changing seasonal climates are projected to increase exposure-linked health impacts and economic vulnerabilities in the agricultural, timber, and manufacturing sectors. By the end of the century, over one-half billion labor hours could be lost from extreme heat-related impacts. Such changes would negatively impact the region's labor-intensive agricultural industry and compound existing social stresses in rural areas related to limited local community capabilities and associated with rural demography, occupations, earnings, literacy, and poverty incidence. Reduction of existing stresses can increase resilience.

Executive Summary

The Southeast includes vast expanses of coastal and inland low-lying areas, the southern portion of the Appalachian Mountains, numerous high-growth metropolitan areas, and large rural expanses. These beaches and bayous, fields and forests, and cities and small towns are all at risk from a changing climate. While some climate change impacts, such as sea level rise and extreme downpours, are being acutely felt now, others, like increasing exposure to dangerous high temperatures, humidity, and new local diseases, are expected to become more significant in the coming decades. While all regional residents and communities are potentially at risk for some impacts, some communities or populations are at greater risk due to their locations, services available to them, and economic situations.

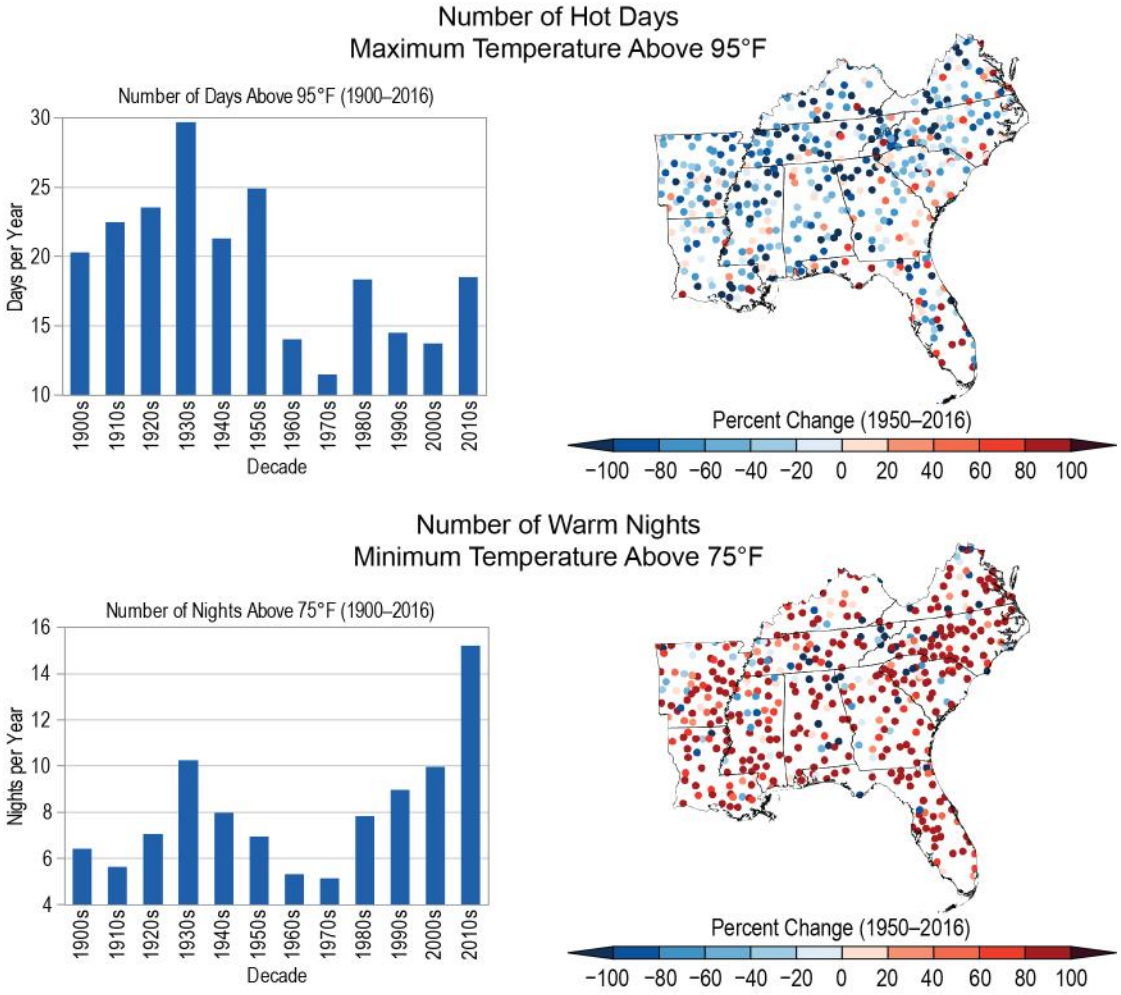
Observed warming since the mid-20th century has been uneven in the Southeast region, with average daily minimum temperatures increasing three times faster than average daily maximum temperatures. The number of extreme rainfall events is increasing. Climate model simulations of future conditions project increases in both temperature and extreme precipitation.

Trends towards a more urbanized and denser Southeast are expected to continue, creating new climate vulnerabilities. Cities across the Southeast are experiencing more and longer summer heat waves. Vector-borne diseases pose a greater risk in cities than in rural areas because of higher population densities and other human factors, and the major urban centers in the Southeast are already impacted by poor air quality during warmer months. Increasing precipitation and extreme weather events will likely impact roads, freight rail, and passenger rail, which will likely have cascading effects across the region. Infrastructure related to drinking water and wastewater treatment also has the potential to be compromised by climate-related events. Increases in extreme rainfall events and high tide coastal floods due to future climate change will impact the quality of life of permanent residents as well as tourists visiting the low-lying and coastal regions of the Southeast. Sea level rise is contributing to increased coastal flooding in the Southeast, and high tide flooding already poses daily risks to businesses, neighborhoods, infrastructure, transportation, and ecosystems in the region.[1,2] There have been numerous instances of intense rainfall events that have had devastating impacts on inland communities in recent years.

The ecological resources that people depend on for livelihoods, protection, and well-being are increasingly at risk from the impacts of climate change. Sea level rise will result in the rapid conversion of coastal, terrestrial, and freshwater ecosystems to tidal saline habitats. Reductions in the frequency and intensity of cold winter temperature extremes are already allowing tropical and subtropical species to move northward and replace more temperate species. Warmer winter temperatures are also expected to facilitate the northward movement of problematic invasive species, which could transform natural systems north of their current distribution. In the future, rising temperatures and increases in the duration and intensity of drought are expected to increase wildfire occurrence and also reduce the effectiveness of prescribed fire practices.[3,4,5,6]

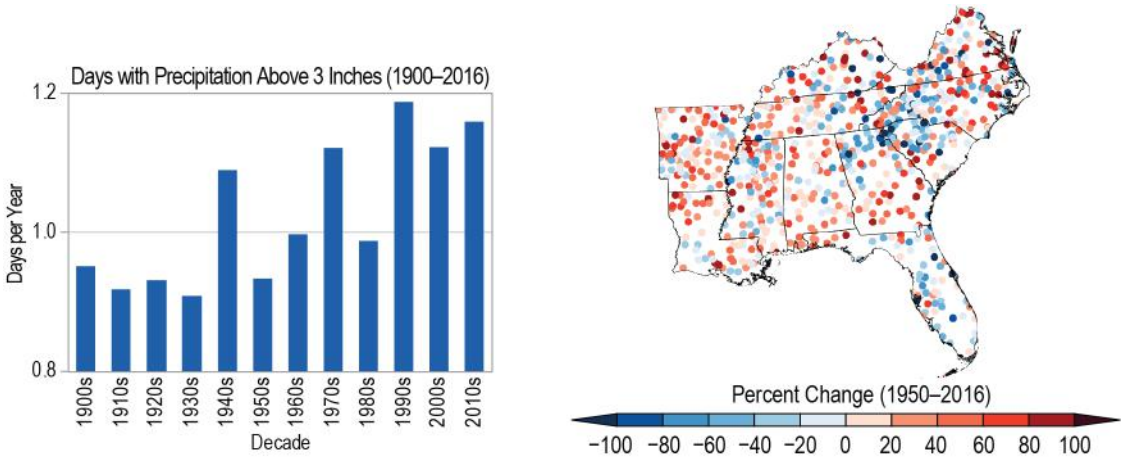
Many in rural communities are maintaining connections to traditional livelihoods and relying on natural resources that are inherently vulnerable to climate changes. Climate trends and possible climate futures show patterns that are already impacting—and are projected to further impact—rural sectors, from agriculture and forestry to human health and labor productivity. Future temperature increases are projected to pose challenges to human health. Increases in temperatures, water stress, freeze-free days, drought, and wildfire risks, together with changing conditions for invasive species and the movement of diseases, create a number of potential risks for existing agricultural systems.[7] Rural communities tend to be more vulnerable to these changes due to factors such as demography, occupations, earnings, literacy, and poverty incidence.[8,9,10] In fact, a recent economic study using a higher scenario (RCP8.5)[11] suggests that the southern and midwestern populations are likely to suffer the largest losses from future climate changes in the United States. Climate change tends to compound existing vulnerabilities and exacerbate existing inequities. Already poor regions, including those found in the Southeast, are expected to continue incurring greater losses than elsewhere in the United States.

Historical Changes in Hot Days and Warm Nights



Sixty-one percent of major Southeast cities are exhibiting some aspects of worsening heat waves, which is a higher percentage than any other region of the country.[12] Hot days and warm nights together impact human comfort and health and result in the need for increased cooling efforts. Agriculture is also impacted by a lack of nighttime cooling. Variability and change in (top) the annual number of hot days and (bottom) warm nights are shown. The bar charts show averages over the region by decade for 1900–2016, while the maps show the trends for 1950–2016 for individual weather stations. Average summer temperatures during the most recent 10 years have been the warmest on record, with very large increases in nighttime temperatures and more modest increases in daytime temperatures, as indicated by contrasting changes in hot days and warm nights. (top left) The annual number of hot days (maximum temperature above 95°F) has been lower since 1960 than the average during the first half of the 20th century; (top right) trends in hot days since 1950 are generally downward except along the south Atlantic coast and in Florida due to high numbers during the 1950s but have been slightly upward since 1960, following a gradual increase in average daytime maximum temperatures during that time. (bottom left) Conversely, the number of warm nights (minimum temperature above 75°F) has doubled on average compared to the first half of the 20th century and (bottom right) locally has increased at most stations. *From Figure 19.1 (Sources: NOAA NCEI and CICS-NC)*.

Historical Change in Heavy Precipitation



The figure shows variability and change in (left) the annual number of days with precipitation greater than 3 inches (1900–2016) averaged over the Southeast by decade and (right) individual station trends (1950–2016). The number of days with heavy precipitation has increased at most stations, particularly since the 1980s. *From Figure 19.3 (Sources: NOAA NCEI and CICS-NC)*

Background

Throughout the southeastern United States, the impacts of sea level rise, increasing temperatures, extreme heat events, heavy precipitation, and decreased water availability continue to have numerous consequences for human health, the built environment, and the natural world. This assessment builds on the above concerns described in the Third National Climate Assessment (NCA3) and includes impacts to urban and rural landscapes as well as natural systems. The impacts from these changes are becoming visible as 1) flooding increases stress on infrastructure, ecosystems, and populations; 2) warming temperatures affect human health and bring about temporal and geographic shifts in the natural environment and landscapes; and 3) wildfires and growing wildfire risk create challenges for natural resource managers and impacted communities.

The Southeast includes vast expanses of coastal and inland low-lying areas, the southern (and highest) portion of the Appalachian Mountains, numerous high-growth metropolitan areas, and large rural expanses. Embedded in these land- and seascapes is a rich cultural history developed over generations by the many communities that call this region home. However, these beaches and bayous, fields and forests, and cities and small towns are all at risk from a changing climate. These risks vary in type and magnitude from place to place, and while some climate change impacts, such as sea level rise and extreme downpours, are being acutely felt now, others, like increasing exposure to dangerously high temperatures—often accompanied by high humidity—and new local diseases, are expected to become more significant in the coming decades. While all regional residents and communities are potentially at risk for some impacts, some communities or populations are at greater risk due to their locations, services available, and economic situations. In fact, a recent economic study using a higher scenario (RCP8.5)[11] suggests that the southern and midwestern populations are likely to suffer the largest losses from projected climate changes in the United States. According to the article, "[b]ecause losses are largest in regions that are already poorer on average, climate change tends to increase preexisting inequality in the United States."[11] Understanding the demographic and socioeconomic composition of racial and ethnic groups in the region is important, because these characteristics are associated with health risk factors, disease prevalence, and access to care, which in turn may influence the degree of impact from climate-related threats.

Historical Climate and Possible Future Climates

The Southeast region experienced high annual average temperatures in the 1920s and 1930s, followed by cooler temperatures until the 1970s. Since then, annual average temperatures have warmed to levels above the 1930s; the decade of the 2010s through 2017 has been warmer than any previous decade (App 5: FAQs, Figure A5.14), both for average daily maximum and average daily minimum temperature. Seasonal warming has varied. The decade of the 2010s through 2017 is the warmest in all seasons for average daily minimum temperature and in winter and spring for average daily maximum temperature. However, for average daily maximum temperature, the summers of the 1930s and 1950s and the falls of the 1930s were warmer on average. The southeastern United States is one of the few regions in the world that has experienced little overall warming of daily maximum temperatures since 1900. The reasons for this have been the subject of much research, and hypothesized causes include both human and natural influences.[13,14,15,16,17] However, since the early 1960s, the Southeast has been warming at a similar rate as the rest of the United States (Ch.

2: Climate, Figure 2.4). During the 2010s, the number of nights with minimum temperatures greater than 75°F was nearly double the long-term average for 1901–1960 (Figure 19.1), while the length of the freeze-free season was nearly 1.5 weeks greater than any other period in the historical record (Figure 19.2). These increases were widespread across the region and can have important effects on both humans and the natural environment.[18] By contrast, the number of days above 95°F has been lower since 1960 compared to the pre-1960 period, with the highest numbers occurring in the 1930s and 1950s, both periods of severe drought (Figure 19.1). The differing trends in hot days and warm nights reflect the seasonal differences in average daily maximum and average daily minimum temperature trends.

Historical Changes in Hot Days and Warm Nights

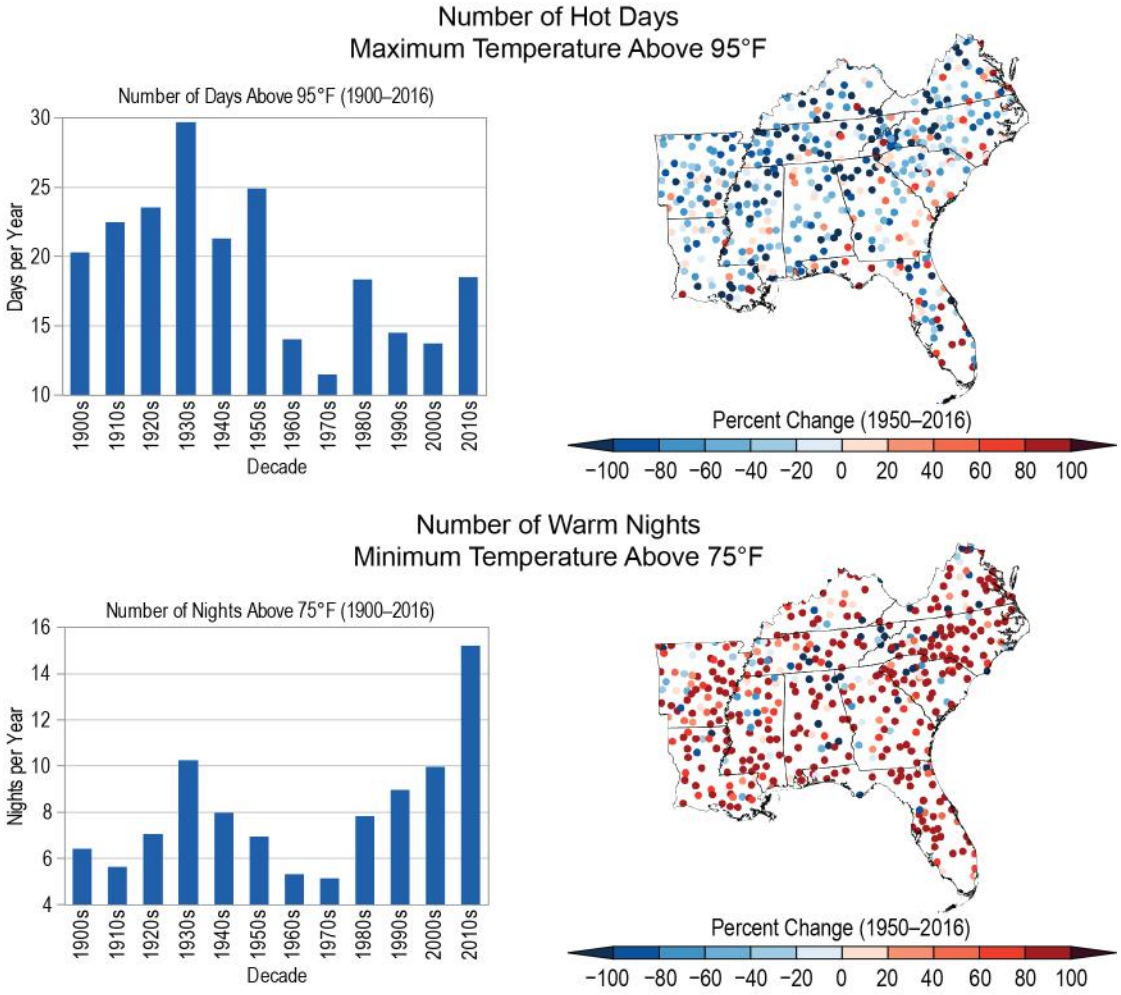


Figure 19.1: Sixty-one percent of major Southeast cities are exhibiting some aspects of worsening heat waves, which is a higher percentage than any other region of the country.[12] Hot days and warm nights together impact human comfort and health and result in the need for increased cooling efforts. Agriculture is also impacted by a lack of nighttime cooling. Variability and change in (top) the annual number of hot days and (bottom) warm nights are shown. The bar charts show averages over the region by decade for 1900–2016, while the maps show the trends for 1950–2016 for individual weather stations. Average summer temperatures during the most recent 10 years have been the warmest on record, with very large increases in nighttime temperatures and more modest increases in daytime temperatures, as indicated by contrasting changes in hot days and warm nights. (top left) The annual number of hot days (maximum temperature above 95°F) has been lower since 1960 than the average during the first half of the 20th century; (top right) trends in hot days since 1950 are generally downward except along the south Atlantic coast and in Florida due to high numbers during the 1950s but have been slightly upward since 1960, following a gradual increase in average daytime maximum temperatures during that time. (bottom left) Conversely, the number of warm nights (minimum temperature above 75°F) has doubled on average compared to the first half of the 20th century and (bottom right) locally has increased at most stations. Sources: NOAA NCEI and CICS-NC.

Historical Change in Freeze-Free Season Length

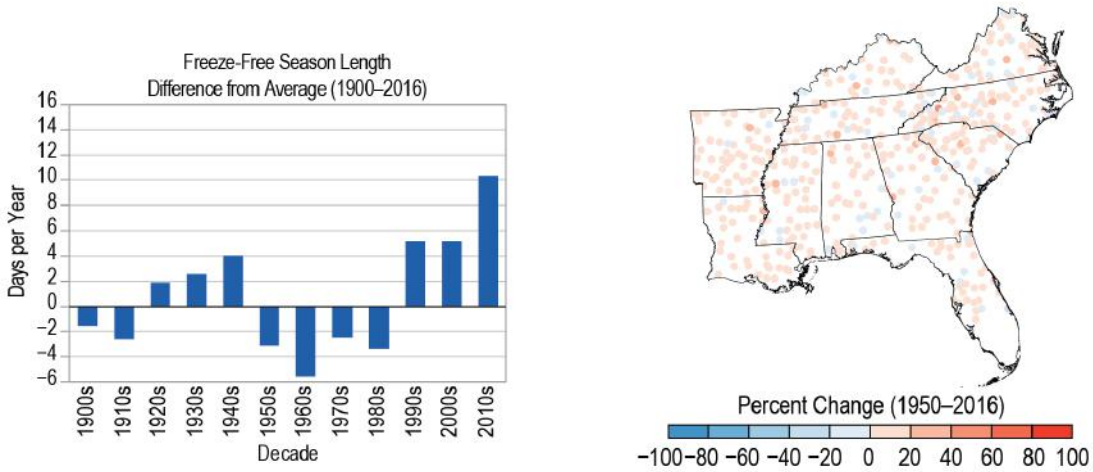


Figure 19.2: The figure shows the variability and change in the length of the freeze-free season. (left) The bar chart shows differences in the length of the freeze-free season by decade (1900–2016) as compared to the long-term average for the Southeast. (right) The map shows trends over 1950–2016 for individual weather stations. The length of the freeze-free season has increased at most stations, particularly since the 1980s. Sources: NOAA NCEI and CICS-NC.

Historical Change in Heavy Precipitation

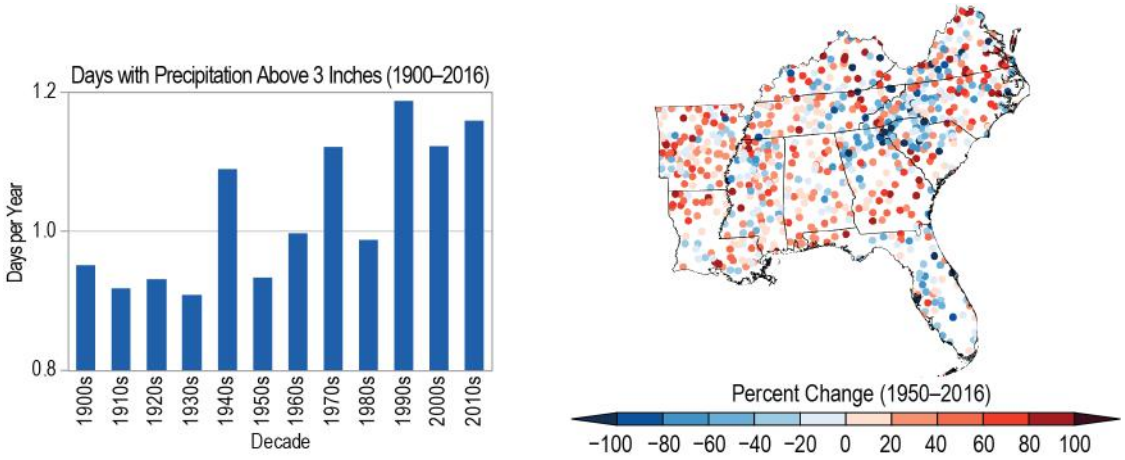


Figure 19.3: The figure shows variability and change in (left) the annual number of days with precipitation greater than 3 inches (1900–2016) averaged over the Southeast by decade and (right) individual station trends (1950–2016). The numbers of days with heavy precipitation has increased at most stations, particularly since the 1980s. Sources: NOAA NCEI and CICS-NC.

The number of extreme rainfall events is increasing. For example, the number of days with 3 or more inches of precipitation has been historically high over the past 25 years, with the 1990s, 2000s, and 2010s ranking as the decades with the 1st, 3rd, and 2nd highest number of events, respectively (Figure 19.3). More than 70% of precipitation recording locations show upward trends since 1950, although there are downward trends at many stations along and southeast of the Appalachian Mountains and in Florida (Figure 19.3).

Climate model simulations of future conditions project increases in temperature and extreme precipitation for both lower and higher scenarios (RCP4.5 and RCP8.5; see Figure 19.5).[13,19] After the middle of the 21st century, however, the projected increases are lower for the lower scenario (RCP4.5). Much larger changes are simulated by the late 21st century under the higher scenario (RCP8.5), which most closely tracks with our current consumption of fossil fuels. Under the higher scenario, nighttime

minimum temperatures above 75°F and daytime maximum temperatures above 95°F become the summer norm and nights above 80°F and days above 100°F, now relatively rare occurrences, become commonplace. Cooling degree days (a measure of the need for air conditioning [cooling] based on daily average temperatures rising above a standard temperature—often 65°F) nearly double, while heating degree days (a measure of the need for heating) decrease by over a third (Figure 19.22). The freeze-free season lengthens by more than a month, and the frequency of freezing temperatures decreases substantially.[20,21]

Key Message 1

Urban Infrastructure and Health Risks

Many southeastern cities are particularly vulnerable to climate change compared to cities in other regions, with expected impacts to infrastructure and human health. The vibrancy and viability of these metropolitan areas, including the people and critical regional resources located in them, are increasingly at risk due to heat, flooding, and vector-borne disease brought about by a changing climate. Many of these urban areas are rapidly growing and offer opportunities to adopt effective adaptation efforts to prevent future negative impacts of climate change.

Rapid Population Shifts and Climate Impacts on Urban Areas

While the Southeast is historically known for having a rural nature, a drastic shift toward a more urbanized region is underway. The Southeast contains many of the fastest-growing urban areas in the country, including a dozen of the top 20 fastest-growing metropolitan areas (by percentage) in 2016.[22] Metropolitan Atlanta has been swiftly growing, adding 69,200 residents in just one year.[23] At the same time, many rural counties in the South are losing population.[24] These trends towards a more urbanized and dense Southeast are expected to continue, creating new climate vulnerabilities but also opportunities to adapt as capacity and resources increase in cities (Ch. 17: Complex Systems). In particular, coastal cities in the Southeast face multiple climate risks, and many planning efforts are underway in these cities. Adaptation, mitigation, and planning efforts are emphasizing "co-benefits" (positive benefits related to the reduction of greenhouse gases or implementation of adaptation efforts) to help boost the economy while protecting people and infrastructure.

Increasing Heat

Cities across the Southeast are experiencing more and longer summer heat waves. Nationally, there are only five large cities that have increasing trends exceeding the national average for all aspects of heat waves (timing, frequency, intensity, and duration), and three of these cities are in the Southeast region—Birmingham, New Orleans, and Raleigh. Sixty-one percent of major Southeast cities are exhibiting some aspects of worsening heat waves, which is a higher percentage than any other region of the country.[12] The urban heat island effect (cities that are warmer than surrounding rural areas, especially at night) adds to the impact of heat waves in cities (Ch. 5: Land Changes, KM 1). Southeastern cities including Memphis and Raleigh have a particularly high future heat risk.[25]

The number of days with high minimum temperatures (nighttime temperatures that stay above 75°F) has been increasing across the Southeast (Figure 19.1), and this trend is projected to intensify, with some areas experiencing more than 100 additional warm nights per year by the end of the century (Figures 19.4 and 19.5). Exposure to high nighttime minimum temperatures reduces the ability of some people to recover from high daytime temperatures, resulting in heat-related illness and death.[26] This effect is particularly pronounced in cities, many of which have urban heat islands that already cause elevated nighttime temperatures.[27] Cities are taking steps to prevent negative health impacts from heat. For example, the Louisville, Kentucky, metro government conducted an urban heat management study and installed 145,000 square feet of cool roofs as part of their goal to lessen the risk of climate change impacts.[28]

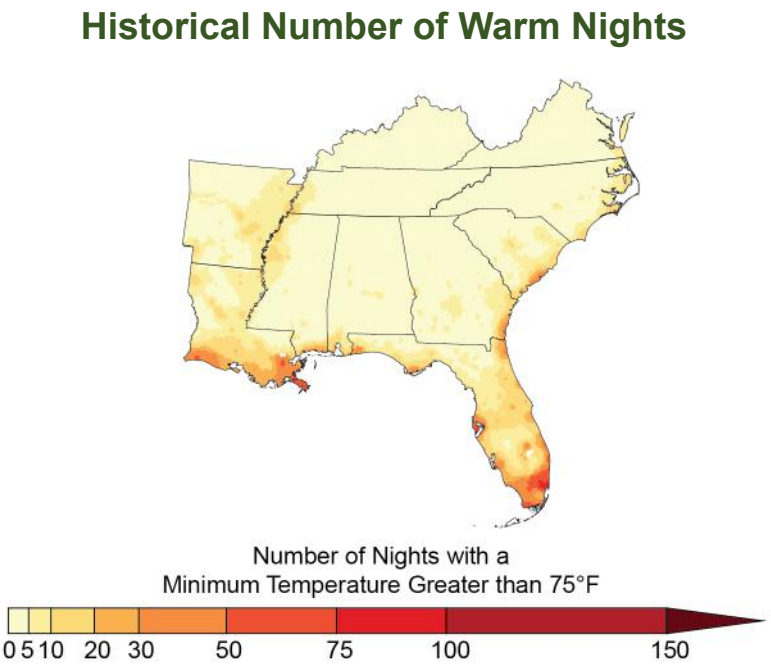


Figure 19.4: The map shows the historical number of warm nights (days with minimum temperatures above 75°F) per year in the Southeast, based on model simulations averaged over the period 1976–2005. Sources: NOAA NCEI and CICS-NC.

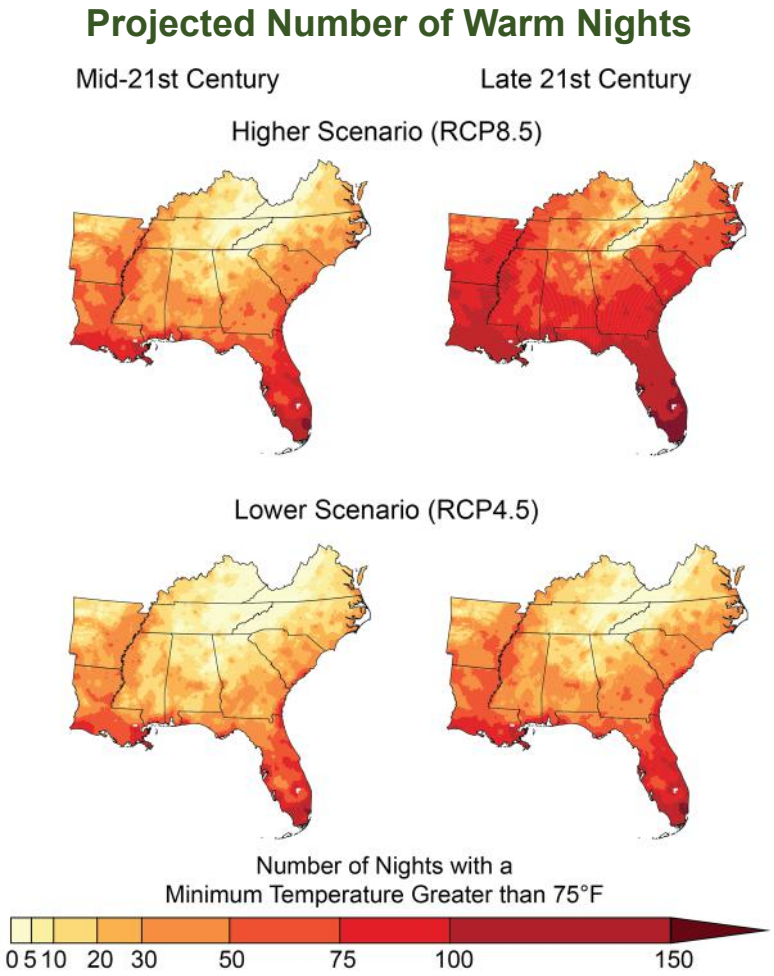


Figure 19.5: The maps show the projected number of warm nights (days with minimum temperatures above 75°F) per year in the Southeast for the mid-21st century (left; 2036–2065) and the late 21st century (right; 2070–2099) under a higher scenario (RCP8.5; top row) and a lower scenario (RCP4.5; bottom row). These warm nights currently occur only a few times per year across most of the region (Figure 19.4) but are expected to become common events across much of the Southeast under a higher scenario. Increases in the number of warm nights adversely affect agriculture and reduce the ability of some people to recover from high daytime temperatures. With more heat waves expected, there will likely be a higher risk for more heat-related illness and deaths. Sources: NOAA NCEI and CICS-NC.

Vector-Borne Disease

The transmission of vector-borne diseases, which are spread by the bite of an animal such as a mosquito or tick, is complex and depends on a number of factors, including weather and climate, vegetation, animal host populations, and human activities (Ch. 14: Human Health, KM 1). Climate change is likely to modify the seasonality, distribution, and prevalence of vector-borne diseases in the Southeast.[29] Vector-borne diseases pose a greater risk in cities than in rural areas because of higher population densities and other human factors (for example, pools of standing water in man-made structures, such as tires or buckets, are breeding grounds for some species of mosquitoes). Climatic conditions are currently suitable for adult mosquitoes of the species *Aedes aegypti*, which can spread dengue, chikungunya, and Zika viruses, across most of the Southeast from July through September (Figure 19.6), and cities in South Florida already have suitable conditions for year-round mosquito activity. The Southeast is the region of the country with the most favorable conditions for this mosquito and thus faces the greatest threat from diseases the mosquito carries.[30] Climate change is expected to make conditions more suitable for transmission of certain vector-borne diseases, including year-round transmission in southern

Florida. Summer increases in dengue cases are expected across every state in the Southeast. Despite warming, low winter temperatures may prevent permanent year-round establishment of the virus across the region.[31] Strategies such as management of urban wetlands have resulted in lower dengue fever risk in Puerto Rico.[32] Similar adaptation strategies have the potential to limit vector-borne disease in southeastern cities, particularly those cities with characteristics similar to Caribbean cities that have already implemented vector control strategies (Ch. 20: U.S. Caribbean).[33,34] The Southeast is also the region with the greatest projected increase in cases of West Nile neuroinvasive disease under both a lower and higher scenario (RCP4.5 and RCP8.5).[35,36]

Air Quality and Human Health

Poor air quality directly impacts human health, resulting in respiratory disease and other ailments. In the Southeast, poor air quality can result from emissions (mostly from vehicles and power plants), wildfires, and allergens such as pollen. The major urban centers in the Southeast are already impacted by poor air quality during warmer months. The Southeast has more days with stagnant air masses than other regions of the country (40% of summer days) and higher levels of fine (small) particulate matter ($PM_{2.5}$), which cause heart and lung disease.[37] There is mixed evidence on the future health impacts of these pollutants. Ozone concentrations would be expected to increase under higher temperatures; however, a variety of factors complicate projections (Ch. 13: Air Quality, KM 1). There are many possible future wind and cloud cover conditions for the Southeast as well as the potential for continued shifts in land-use patterns, demographics and population geography, and vehicle and power plant emissions standards. Increases in precipitation and shifts in wind trajectories may reduce future health impacts of ground level ozone in the Southeast,[35] but warmer and drier autumns are expected to result in a lengthening of the period of ozone exposure.[38] Warmer August temperatures in the Southeast from 1988 to 2011 were associated with increased human sensitivity to ground-level ozone.[39]

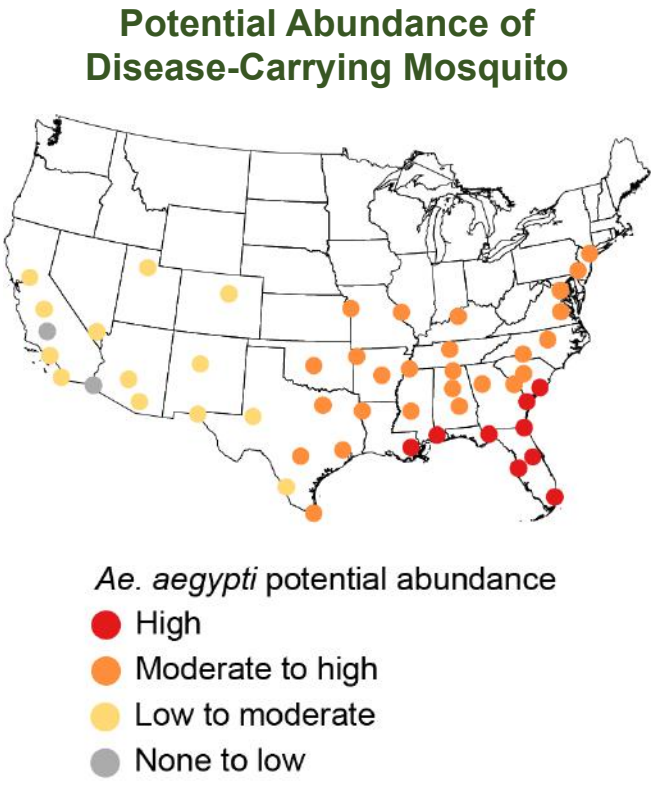


Figure 19.6: The map shows current suitability for the *Aedes aegypti* mosquito in July in 50 different cities. *Aedes aegypti* mosquitoes can spread several important diseases, including dengue fever, chikungunya, and Zika fever. The Southeast is the region of the country with the greatest potential mosquito activity. Warming temperatures have the potential to expand mosquito habitat and disease risk. Source: adapted from Monaghan et al. 2016.[30]

The fast growth rate of urban areas in the Southeast contributes to aeroallergens, which are known to cause and exacerbate respiratory diseases such as asthma. Urban areas have higher concentrations of CO_2, which causes allergenic plants, such as ragweed, to grow faster and produce more pollen than in rural areas.[40] Continued rising temperatures and atmospheric CO_2 levels are projected to further contribute to aeroallergens in cities (Ch. 13: Air Quality, KM 3).

Infrastructure

Infrastructure, particularly roads, bridges, coastal properties, and urban drainage, is vulnerable to climate change and climate-related events (see Key Message 2) (see also Ch. 3: Water, KM 2; Ch. 11: Urban, KM 2; Ch. 12: Transportation, KM 1).[41] By 2050, the Southeast is the region expected to have the most vulnerable bridges.[35] An extreme weather vulnerability assessment conducted by the Tennessee Department of Transportation found that the urban areas of Memphis and Nashville had the most at-risk transportation infrastructure in the state.[42] Increasing precipitation and extreme weather events will likely impact roads, freight rail, and passenger rail, especially in Memphis, which will likely have cascading effects across the region.[43] Transit infrastructure, such as the rail lines of the Metropolitan Atlanta Rapid Transit Authority (MARTA), are also at risk. As a result, MARTA has begun to identify vulnerable assets and prioritize improvements to develop a more resilient system.[44]

Many cities across the Southeast are planning for the impacts sea level rise is likely to have on their infrastructure (see Case Study "Charleston, South Carolina, Begins Planning and Reinvesting" and Key Message 2). Flood events in Charleston, South Carolina, have been increasing, and by 2045 the city is projected to face nearly 180 tidal floods (flooding in coastal areas at high tide) per year, as compared to 11 floods per year in 2014.[45] These floods affect tourism, transportation, and the economy as a whole. The city has responded by making physical modifications, developing a more robust disaster response plan, and improving planning and monitoring prior to flood events.

Infrastructure related to drinking water treatment and wastewater treatment may be compromised by climate-related events (Ch. 3: Water, KM 2). Water utilities across the Southeast are preparing for these impacts. Tampa Bay Water, the largest wholesale water utility in the Southeast, is coordinating with groups including the Florida Water and Climate Alliance to study the impact of climate change on its ability to provide clean water in the future.[46,47] Spartanburg Water, in South Carolina, is reinforcing the ability of the utility to "cope with, and recover from disruption, trends and variability in order to maintain services."[48] Similarly, the Seminole Tribe of Florida, which provides drinking and wastewater services, assessed flooding and sea level rise threats to their water infrastructure and developed potential adaptation measures.[49] The development of "green" water infrastructure (using natural hydrologic features to manage water and provide environmental and community benefits), such as the strategies promoted in the City of Atlanta Climate Action Plan, is one way to adapt to future water management needs. Implementation of these strategies has already resulted in a reduction in water consumption in the city of Atlanta, relieving strain on the water utility and increasing resilience.[50]

There are still gaps in knowledge regarding the potential effects of climate change on cities across the Southeast. Cross-disciplinary groups such as the Georgia Climate Project (http://www.georgiaclimateproject.org) are developing research roadmaps that can help to prioritize research and action with relevance to policymakers, practitioners, and scientists.

Key Message 2

Increasing Flood Risks in Coastal and Low-Lying Regions

The Southeast's coastal plain and inland low-lying regions support a rapidly growing population, a tourism economy, critical industries, and important cultural resources that are highly vulnerable to climate change impacts. The combined effects of changing extreme rainfall events and sea level rise are already increasing flood frequencies, which impacts property values and infrastructure viability, particularly in coastal cities. Without significant adaptation measures, these regions are projected to experience daily high tide flooding by the end of the century.

Sea Level Rise Is Contributing to Increased Coastal Flooding in the Southeast

Average global sea level (or global mean sea level; GMSL) has risen about 8–9 inches since 1880, with about 3 inches of that rise occurring since 1990.[51,52] This recent increase in the rate of rise is projected to accelerate in the future due to continuing temperature increases and additional melting of land ice.[51] This recent global rate increase, combined with the local effects of vertical land motion (sinking) and oceanographic effects such as changing ocean currents, has caused some areas in the Southeast to experience even higher local rates of sea level rise than the global average.[53,54,55,56,57,58,59] Analyses at National Oceanic and Atmospheric Administration (NOAA) tide gauges show as much as 1 to 3 feet of local relative sea level rise in the past 100 years in low-lying areas of the Southeast.[54,59] This recent rise in local relative sea level has caused normal high tides to reach critical levels that result in flooding in many coastal areas in the region.

Monthly and seasonal fluctuations in high tide levels are caused by a combination of astronomical factors (sun and moon gravitational attraction) and non-astronomical factors such as geomorphology (landscape of the area), as well as meteorological (weather) conditions. The highest tides of the year are generally the perigean, or spring, tides, which occur when the moon is full or new and is closest to the Earth. These perigean tides, also known as "king tides," occur twice a year and in many cities are causing what has been called "nuisance" or "recurrent" flooding (referred to herein as high tide flooding). These floods can cause problems ranging from inconvenient to life changing. While the challenges brought on by rising perigean tides are diverse, important examples include increasingly frequent road closures, excessive water in storm water management systems, and deterioration of infrastructure such as roads and rail from saltwater. NOAA's National Weather Service (NWS) issues coastal flood advisories and warnings when water levels at tide gauges are expected to exceed flood thresholds. These thresholds correspond to discrete water levels relative to NOAA tide gauges.

Recent analyses of historical water levels at many NOAA tide gauges has shown an increase in the number of times that these warning thresholds were exceeded compared to the past. Annual occurrences of high tide coastal flooding have increased 5- to 10-fold since the 1960s in several low-lying coastal cities in the Southeast (Figure 19.7).[51,60] In 2015, several Southeast coastal cities experienced all-time records of coastal flooding occurrences, including Wilmington, NC (90 days), Charleston, SC (38 days), Mayport, FL (19 days), Miami, FL (18 days), Key West, FL (14 days), and Fernandina Beach, FL (7 days). These flooding occurrences increased more than 50% in 2015 compared to 2014.[58] In 2016, three all-time records were either tied (14 days at Key West,

FL) or broken (50 days at Charleston, SC, and 38 days at Savannah, GA). The Miami area nearly matched the 2015 record of 18 days.[61] This increase in high tide flooding frequency is directly tied to sea level rise. For example, in Norfolk, Virginia, local relative sea level rise has led to a fourfold increase in the probability of exceeding NWS thresholds compared to the 1960s (Figure 19.8). High tide flooding is now posing daily risks to businesses, neighborhoods, infrastructure, transportation, and ecosystems in the Southeast.[1,2]

Global sea level is very likely to rise by 0.3–0.6 feet by 2030, 0.5–1.2 feet by 2050, and 1.0–4.3 feet by 2100 under a range of scenarios from very low (RCP2.6) to high (RCP8.5),[51,52,62] which would result in increases in both the depth and frequency of coastal flooding (Figure 19.7).[51] Under higher emissions scenarios (RCP8.5), global sea level rise exceeding 8 feet (and even higher in the Southeast) by 2100 cannot be ruled out.[51] By 2050, many Southeast cities are projected to experience more than 30 days of high tide flooding regardless of scenario.[63] In addition, more extreme coastal flood events are also projected to increase in frequency and duration.[60] For example, water levels that currently have a 1% chance of occurring each year (known as a 100-year event) will be more frequent with sea level rise. This increase in flood frequency suggests the need to consider revising flood study techniques and standards that are currently used to design and build coastal infrastructure.

Higher sea levels will cause the storm surges from tropical storms to travel farther inland than in the past, impacting more coastal properties. The combined impacts of sea level rise and storm surge in the Southeast have the potential to cost up to $60 billion each year in 2050 and up to $99 billion in 2090 under a higher scenario (RCP8.5).[35] Even under a lower scenario (RCP4.5), projected damages are $56 and $79 billion in 2050 and 2090, respectively (in 2015 dollars, undiscounted).[35] Florida alone is estimated to have a 1-in-20 chance of having more than $346 billion (in 2011 dollars) in property value (8.7%) below average sea level by 2100 under a higher scenario (RCP8.5).[64] An assessment by the Florida Department of Health determined that 590,000 people in South Florida face "extreme" or "high" risk from sea level rise, with 125,000 people living in these areas identified as socially vulnerable and 55,000 classified as medically vulnerable.[65] In addition to causing direct injury, storm surge and related flooding can impact transportation infrastructure by blocking or flooding roads and affecting access to healthcare facilities (Ch. 12: Transportation, KM 1). Marine transportation can be impacted as well. Large ports in the Southeast, such as Charleston, Savannah, and Jacksonville, and the rails and roads that link to them, are particularly vulnerable to both coastal flooding and sea level rise (Ch. 12: Transportation, KM 1; Ch. 8: Coastal, KM 1). The Port of Jacksonville provides raw material for industries, food, clothes, and essential goods to Puerto Rico, thus impacting the U.S. Caribbean region, as well (Ch. 20: U.S. Caribbean, KM 3). It is estimated that with a meter (about 3.3 feet) of sea level rise, the Southeast would lose over 13,000 recorded historic and prehistoric archaeological sites and more than 1,000 locations currently eligible for inclusion on the National Register of Historic Places.[66] This includes many historic buildings and forts in cities like Charleston, Savannah, and St. Augustine.

Annual Number of High Tide Flooding Days

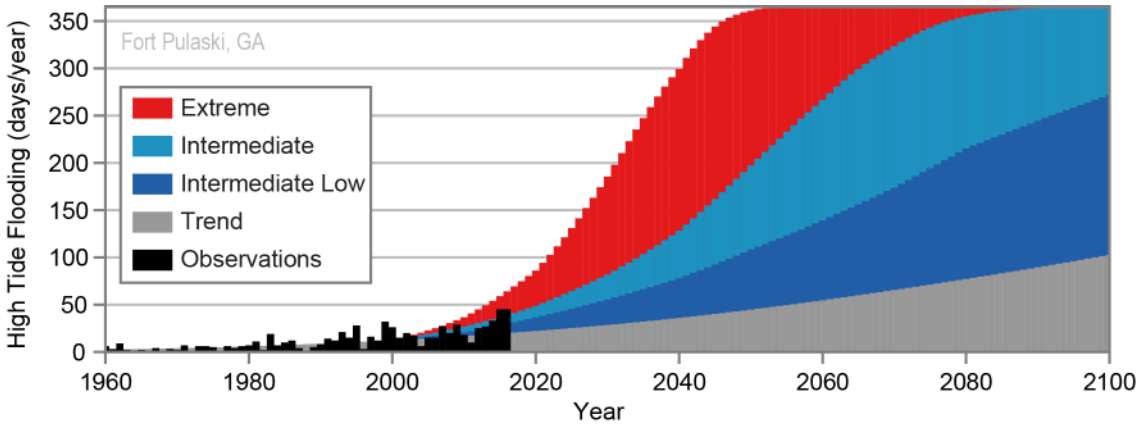


Figure 19.7: The figure shows the annual number of days experiencing high tide floods based on observations for 1960–2016 for Fort Pulaski, near Savannah, Georgia (black), and projected increases in the number of annual flood events based on four future scenarios: a continuation of the current relative sea level trend (gray) and the Intermediate-Low (dark blue), Intermediate (light blue), and Extreme (red) sea level rise scenarios. See Sweet et al. (2017)[51] and Appendix 3: Data & Scenarios for additional information on projection and trend data. Source: adapted from Sweet and Park 2014.[63]

Range of Daily Highest Water Levels in Norfolk, Virginia

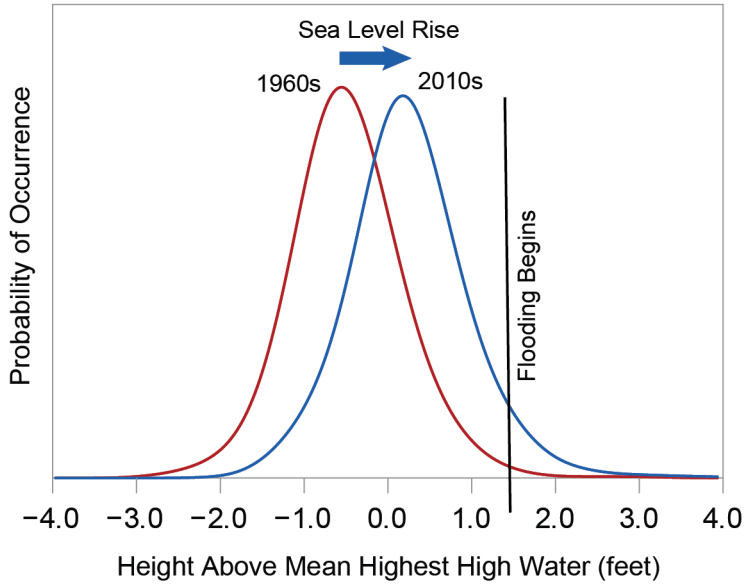


Figure 19.8: The curves in this figure show a range of daily Mean Higher High Water (MHHW) levels in Norfolk, Virginia (Sewells Point), for the 1960s and 2010s. Local sea level rise has shifted the curve closer to the point where high tide flooding begins (based on warning thresholds established by the National Weather Service). This shows why many more high tide flood events occur now than they did in the past (increase of 6 flood days per year). Source: adapted from Sweet et al. 2017.[52]

Case Study: Charleston, South Carolina, Begins Planning and Reinvesting for Sea Level Rise

The main crosstown traffic artery in Charleston, South Carolina (U.S. 17 Septima Clark Parkway–crosstown), has historically been susceptible to flooding events (Figure 19.9). Charleston experienced all-time record high tide flood occurrences in 2015 (38 days) and 2016 (50 days).[52,58] By 2045, Charleston is projected to experience up to 180 high tide flood events a year.[1] The City of Charleston estimated that each flood event that affects the crosstown costs $12.4 million (in 2009 dollars). Over the past 50 years, the resultant gross damage and lost wages have totaled more than $1.53 billion (dollar year not specified). As a result, Charleston has developed a Sea Level Rise Strategy that plans for 50 years out based on moderate sea level rise scenarios (Figure 19.10) and that reinvests in infrastructure, develops a response plan, and increases readiness.[45] As of 2016, the City of Charleston has spent or set aside $235 million (in 2015 dollars) to complete ongoing drainage improvement projects (Figure 19.9) to prevent current and future flooding.

Figure 19.9: (left) U.S. Highway 17 (Septima Clark Parkway—crosstown) in Charleston, South Carolina, during a flood event. Floodwaters can get deep enough to stall vehicles. (right) Market Street drainage tunnel being constructed in Charleston, South Carolina, as part of a drainage improvement project to prevent current and future flooding. This tunnel crosses a portion of downtown Charleston 140 feet underground and is designed to rapidly convey storm water to the nearby Ashley River. Photo credit: City of Charleston 2015.[45]

Projected Sea Level Rise for Charleston, South Carolina

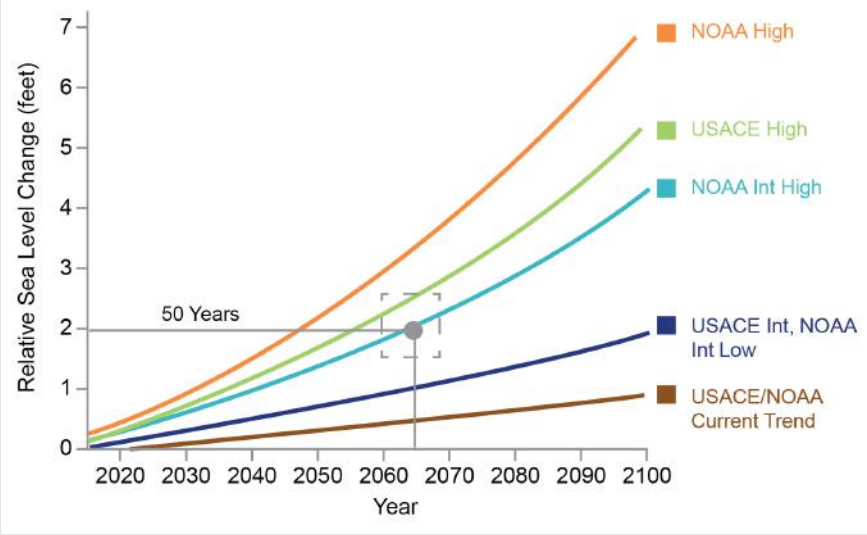


Figure 19.10: The City of Charleston Sea Level Rise Strategy calls for a 50-year outlook, based on existing federal sea level change projections in 2015 (colored curves), and calls for using a range of 1.5–2.5 feet of sea level rise (dashed box). A 1.5-foot increase will be used for short-term, less vulnerable investments, such as a parking lot. A 2.5-foot increase will be used for critical, longer-term investments, such as emergency routes and public buildings. This 1-foot range was chosen to approximate the average of these projections in 2065. Source: City of Charleston 2015.[45]

Many of the older historical coastal cities in the Southeast were built just above the current Mean Higher High Water (MHHW) level (the average height of the higher of the two daily high tides at a given location), with a gravity-driven drainage system designed to drain rainwater into the tidal estuaries. As sea levels have risen locally in the last one hundred years, the storm water systems in these areas are no longer able to perform as designed. When these cities experience high tide coastal flooding due to perigean tides, the tidewater enters the storm water system, which prevents rainwater from entering storm drains and causes increased impacts from flooding. In the future, the gravity-driven nature of many of these systems may cease to function as designed, causing rainwater to flood streets and neighborhoods until the tide lowers and water can drain normally. Cities such as Charleston and Miami have already begun to improve storm water infrastructure and explore natural and nature-based infrastructure design to reduce future flood risk.

Much of the Southeast region's coast is bordered by large expanses of salt marsh and barrier islands. Long causeways with intermittent bridges to connect the mainland to these popular tourism destinations were built decades ago at only a few feet above MHHW. Sea level rise has put these transportation connection points at risk. High tide coastal flooding has started to inundate these low-lying roads, restricting access during certain times of the day and causing public safety concerns. The U.S. East Coast, for example, already has 7,508 miles of roadways, including over 400 miles of interstate roadways, currently threatened by high tide coastal flooding (Ch. 12: Transportation, KM 1 and Figure 12.2).

Sea level rise is already causing an increase in high tide flood events in the Southeast region and is adding to the impact of more extreme coastal flooding events. In the future, this flooding is projected to become more serious, disruptive, and costly as its frequency, depth, and inland extent grow with time (Ch. 12: Transportation, KM 1).[52,63,67,68]

Case Study: A Lesson Learned for Community Resettlement: Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw Tribe

Coastal communities in the Southeast are already experiencing impacts from higher temperatures, sea level rise, increased flooding, and extreme weather events.[69,70,71,72] Several communities in the United States are already discussing the complexities of relocation; most are tribal and Indigenous communities.[73] Some have chosen to stay in their homelands, while others have few options but to relocate (Ch. 15: Tribes, KM 3).

Isle de Jean Charles is a narrow island in the bayous of South Terrebonne Parish, Louisiana, and home to the Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw, a tribal community already living the day-to-day impacts of land loss, sea level rise, and coastal flooding. The island has lost 98% of its landmass since 1955 and has only approximately 320 acres (approximately 1/2 square mile) remaining. The population living on the Island has fallen from 400 to 85 people. The decline is due in large part to land loss and flooding driven by climate change, extreme weather, and unsustainable development practices, which stem from oil and gas production, extraction, and water-management practices.[74] This process has resulted in family separation, spreading them across southern Louisiana.[75] In addition, the Tribe continues to lose parts of its livelihood and culture, including sacred places, cultural sites and practices, healing plants, traditional foods, and lifeways.[76]

Case Study: A Lesson Learned for Community Resettlement: Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw Tribe, *continued*

The Third National Climate Assessment[77] discussed the initial plans for resettlement of the Isle de Jean Charles community. Recently, after nearly 20 years of tribal persistence and two previous efforts, the U.S. Department of Housing and Urban Development (HUD) through the National Disaster Resilience Competition,[78] along with technical assistance from The Rockefeller Foundation, awarded the State of Louisiana $48 million (in 2016 dollars) to implement the Tribe's resettlement plan: a community-driven, culturally appropriate, sustainable development-based plan. It was developed in partnership with the Lowlander Center, a local nongovernmental organization with a long-standing relationship with the Tribe and other scientists, researchers, and planners. The award provides the Tribe with a historic opportunity to reunite a community.[79] While the application to relocate was initiated by the Tribe, the relocation funds now are for all residents of Isle de Jean Charles, according to the Louisiana State Office of Community Development.[75]

Figure 19.11: Chantel Comardelle, Isle de Jean Charles Tribe's Executive Secretary, leads a discussion at a community meeting for the Tribe's resettlement planning process in Pointe-aux-Chenes, Louisiana, on January 18, 2016. The meeting was supported by the Lowlander Center. Photo credit: The Lowlander Center Team.

The resettlement plan is expected to be implemented by 2022 with the inclusion of many facilities in the new location to revitalize the tribal community, including a tribal center and a healthcare facility. The Tribe's experience highlights how success can be achieved when at-risk communities are engaged in the resettlement planning process from the beginning to ensure long-term successful relocation and maintain community integrity.[80] It also highlights an opportunity for institutions to evolve in more flexible ways to accommodate the growing number of communities that may need to relocate.

Extreme Rainfall Events Are Contributing to Increased Inland and Coastal Flooding

Extreme rainfall events have increased in frequency and intensity in the Southeast, and there is *high confidence* they will continue to increase in the future (Figure 19.3).[19] The region, as a whole, has experienced increases in the number of days with more than 3 inches of precipitation (Figure 19.3) and a 16% increase in observed 5-year maximum daily precipitation (the amount falling in an event expected to occur only once every 5 years).[19] Both the frequency and severity of extreme precipitation events are projected to continue increasing in the region under both lower and higher scenarios (RCP4.5 and RCP8.5). By the end of the century under a higher scenario (RCP8.5), projections indicate approximately double the number of heavy rainfall events (2-day precipitation events with a 5-year return period) and a 21% increase in the amount of rain falling on the heaviest precipitation days (days with a 20-year return period).[19,81] These projected increases would directly affect the vulnerability of the Southeast's coastal and low-lying areas. Natural resources (see Key Message 3),

industry, the local economy, and the population of the region are at increasing risk to these extreme events.

Across the Southeast since 2014, there have been numerous examples of intense rainfall events—many approaching levels that would be expected to occur only once every 500 years[82,83]—that have made state or national news due to the devastating impact they had on inland communities. Of these events, four major inland flood events have occurred in just three years (2014–2016) in the Southeast, causing billions of dollars in damages and loss of life (see Table 19.1 and Case Study "Coastal and Inland Impacts of Extreme Rainfall").[84]

A closer look at the August 2016 event in Louisiana provides an example of how vulnerable inland communities in the Southeast region are to these extreme rainfall events. Between August 11–15 2016, nearly half of southern Louisiana received at least 12–14 inches of rainfall. While urban areas such as Baton Rouge and Lafayette were hit the hardest, receiving upwards of 30 inches in a few days, coastal locations were also inundated with up to 20 inches of rain. Rainfall totals across the region exceeded amounts that would be expected to occur once every 1,000 years (or a less than 0.1% annual probability of occurrence), causing the Amite and Comite Rivers to surge past their banks and resulting in some 50,000 homes across the region filling with more than 18 inches of water.[85] Nearly 10 times the number of homes received major flooding (18 inches or more) during this event compared to a historic 1983 flood in Baton Rouge, and the damage resulted in more than 2 million cubic yards of curbside debris from cleaning up homes (enough to fill over 600 Olympic-sized pools).[86] A preceding event in northern Louisiana on March 8–12, 2016, caused $2.4 billion in damages (in 2017 dollars; $2.3 billion in 2015 dollars) and five casualties,[84] illustrating that inland low-lying areas in the Southeast region are also vulnerable to flooding impacts. Events of such magnitudes are projected to become more likely in the future due to a changing climate,[19,87] putting more people in peril from future floods. Existing flood map boundaries do not account for future flood risk due to the increasing frequency of more intense precipitation events, as well as new development that would reduce the floodplain's ability to manage storm water. As building and rebuilding in flood-prone areas continue, the risks of the kinds of major losses seen in these events will continue to grow.

The growing number of extreme rainfall events is stressing the deteriorating infrastructure in the Southeast. Many transportation and storm water systems have not been designed to withstand these events. The combined effects of rising numbers of high tide flooding and extreme rainfall events, along with deteriorating storm water infrastructure, are increasing the frequency and magnitude of coastal and lowland flood events.[45,88,89,90]

Billion-Dollar Flood Events in the Southeast, 2014–2016

Event	Date	Damages	Casualties
Southeast tornadoes and flooding (FL, AL, AR)	April 27–28, 2014	$1.8 Billion	33
South Carolina record flooding	October 1–5, 2015	$2.1 Billion	25
Hurricane Matthew	October 7–9, 2016	$10.1 Billion	49
Louisiana flooding (Baton Rouge)	August 11–15, 2016	$10.1 Billion	13

Table 19.1: Values are Consumer Price Index adjusted and are in 2017 dollars. Source: NOAA NCEI 2017.[84]

The recent increases in flood risk have led many cities and counties to take adaptive actions to reduce these effects. Four counties in Southeast Florida formed a climate compact in 2010 to address climate change impacts, including sea level rise and high tide flooding.[91] Recently updated in 2017, their climate action plan was one of the first intergovernmental collaborations to address climate change, adaptation, and mitigation in the country. Since then, cities like Charleston, South Carolina, have started to invest in flood management activities (see Case Study "Charleston, South Carolina, Begins Planning and Reinvesting"). Other examples include Miami Beach, Florida, which has a multiyear, $500-million program to raise public roads and seawalls and improve storm water drainage.[92] Norfolk, Virginia, has begun comprehensive planning to fix its high tide flooding issues.[93] Biloxi, Mississippi, has put in place several adaptation strategies to lessen the future impacts, including enacting a new building code that requires elevating structures an additional one foot above the base flood elevation.[94] Tybee Island, Georgia, has developed a sea level rise adaptation plan with recommendations to flood-proof a 5.5-mile stretch of their sole access causeway, replace two vulnerable bridges, and retrofit their existing storm water infrastructure to improve drainage.[95] In response to the 2016 flooding, eight parishes in the Acadiana region of Louisiana came together to collaborate at a watershed level, pooling their federal hazard mitigation grant funding to support projects across the Teche-Vermilion watershed. This is the only watershed-level hazard mitigation collaboration of this kind happening in the state and has the support of the Federal Emergency Management Agency (FEMA), the Governor's Office of Homeland Security and Emergency Preparedness, and the Louisiana Office of Community Development.[96]

Many communities in the Southeast also participate in FEMA's Community Rating System (CRS) program, which provides reduced flood insurance premiums to communities that go above and beyond the minimum National Flood Insurance Program regulation standards.[97] Many communities require a safety factor, also known as freeboard, expressed as feet above the base flood elevation, for construction in special flood hazard areas. Several Southeast communities—such as Hillsborough and Pinellas Counties, Florida; Biloxi, Mississippi; Chatham County, Georgia; and Myrtle Beach, South Carolina—have earned low CRS classes (5 on a scale of 1–10, with 1 being the best or most insurance premium discount) by implementing freeboard and other regulations that exceed the minimum standards.[97]

Case Study: Coastal and Inland Impacts of Extreme Rainfall

In October 2015, an extreme rainfall event impacted both inland and coastal South Carolina, leading to the largest flood-related disaster in the state since Hurricane Hugo struck in 1989. The October 2015 event is among a series of devastating precipitation events that have occurred across the Southeast in recent years. From October 1–5, 2015, deep tropical moisture combined with a slow-moving (stalled) upper-level low pressure system to pump moisture into South Carolina's coastal and interior regions. Much of the affected region received between 10 and 26 inches of rain over the 4-day event, breaking many all-time precipitation records (Figure 19.12). Mount Pleasant, located on South Carolina's coast, received 26.88 inches of rain, which is an extremely rare event. The rainfall sparked inland flooding that led to three dam breaches and the destruction of countless roads and homes (see Figure 19.13 showing flash flooding impacts to inland roads). Roughly 52,000 residents applied for disaster relief, and 160,000 homes sustained some type of damage. At the coast, a combination of high tide and heavy rain caused significant flooding in downtown Charleston. A high tide of 2.38 feet above Mean Higher High Water (MHHW) occurred in the afternoon of October 3. This was the seventh highest tide ever recorded in Charleston Harbor and the highest since Hurricane Hugo in 1989. Under future climate scenarios, the combination of extreme precipitation and higher tides due to local sea level rise will likely cause more frequent events of this intensity and magnitude.[98]

Case Study: Coastal and Inland Impacts of Extreme Rainfall, *continued*

October 2015 Extreme Rainfall Event

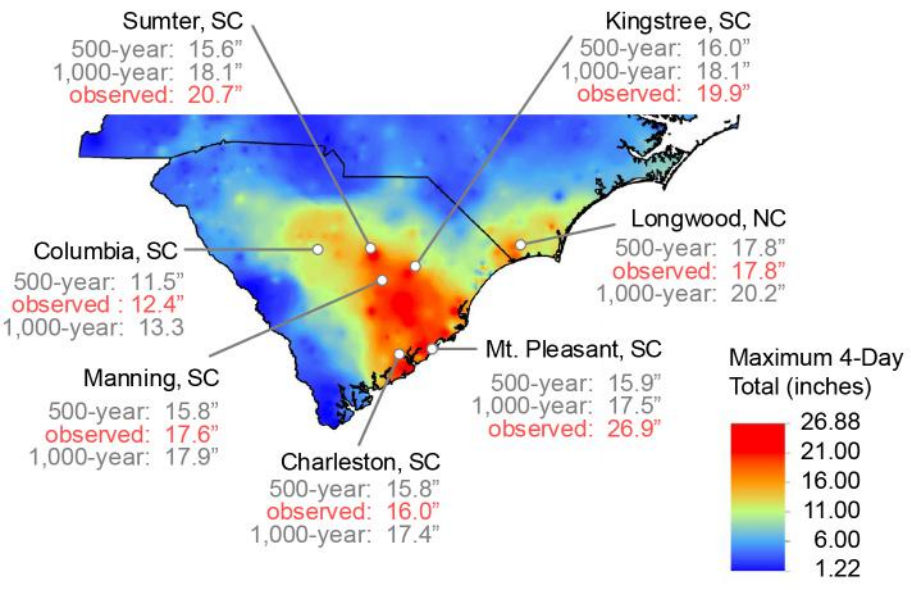


Figure 19.12: The map shows rainfall totals from the October 2015 South Carolina flood event. Red colors in the map indicate areas that received excessive rainfall totals that broke all-time records. Some of these totals exceeded the 500-year and 1,000-year return period amounts (rainfall amounts that would be expected to have only a 0.2% or 0.1% chance of occurring in a given year). Extreme precipitation events will likely increase in frequency in the Southeast. Source: CISA 2015.[98]

Figure 19.13: Many roads became impassable in the inland areas of South Carolina as a result of the October 2015 extreme rainfall event. This photo shows a neighborhood in North Charleston after the event with knee-deep flooding. Photo credit: Ryan Johnson (CC BY-SA 2.0).

Increases in extreme rainfall events and high tide coastal floods due to future climate change could impact the quality of life of permanent residents as well as tourists visiting the low-lying and coastal regions of the Southeast. Recent social science studies have indicated that people may migrate from many coastal communities that are vulnerable to the impacts of sea level rise, high tide flooding, saltwater intrusion, and storm surge.[71] Even though many communities are starting to develop adaptation strategies to address current flooding issues, many adaptation strategies are not being designed for longer time horizons and more extreme worst-case climate scenarios.[1,67]

The 2017 Hurricane Season

For the United States, 2017 was a historic year for weather and climate disasters, with widespread impacts and lingering costs. While 2017 tied the previous record year of 2011 for the total number of billion-dollar weather and climate disasters—16—the year broke the all-time previous record high costs by reaching $306.2 billion in damages (in 2017 dollars; $297 billion in 2015 dollars). The previous record year was 2005 with a total of $214.8 billion (in 2017 dollars; $208.4 billion in 2015 dollars), which included the impacts of Hurricanes Dennis, Katrina, Rita, and Wilma.[99]

In 2017, Hurricane Irma was one of three major hurricanes to make landfall in the United States and territories, with the most significant impacts occurring in the Southeast region. Irma was a Category 4 storm with 130 mph wind speeds when it made landfall at Cudjoe Key, Florida (20 miles north of Key West). Storm surge inundations at Cudjoe and the surrounding Keys were between 5 and 8 feet.[100] Prior to landfall in Florida, Irma caused significant damage in the U.S. Virgin Islands and parts of Puerto Rico as a Category 5 hurricane with 185 mph wind speeds (see Ch. 20: U.S. Caribbean, Box 20.1 and KM 5).[84]

Irma's intensity was impressive by any measure. According to the National Weather Service, Hurricane Irma was only the fifth hurricane with winds of 185 mph or higher in the whole of the Atlantic Basin since reliable record keeping began, and it was the strongest observed hurricane in the open Atlantic Ocean.[101] For three days, the storm maintained maximum sustained winds of 185 miles per hour, the longest observed duration in the satellite era.[101,102] Not only was Irma extremely strong, it was also very large with tropical storm force winds reaching as far away as 400 miles from the hurricane's center and driving hurricane force winds up to 80 miles away.[101] Two factors supported Irma's strength: the very warm waters it passed over, which exceeded 86°F,[102] and the light winds Irma encountered in the upper atmosphere (Figure 19.14).[101] High-intensity hurricanes such as Irma are expected to become more common in the future due to climate change.[103] Rapid intensification of storms is also more likely as the climate warms,[104] even though there is also some historical evidence that the same conditions that lead to this intensification also act to weaken hurricane intensity near the U.S. coast, but it is unclear whether this relationship will continue as the climate warms further (see Kossin et al. 2017,[103] Box 9.1).

The storm tracked up the west coast of Florida, impacting both coasts of the Florida peninsula with 3–5 feet of inundation from Cape Canaveral north to the Florida–Georgia border and even further, impacting coastal areas of Georgia and South Carolina with high tides and storm surge that reached 3–5 feet. Inland areas were also impacted by winds and heavy rains with river gauges and high-water marks showing upwards of 2–6 feet above ground level.[100] The winds eventually fell below tropical storm strength near Columbus, Georgia. Even though the wind speed fell below tropical storm strength, many communities along the coasts of Florida, Georgia,

North and South Carolina, and Virginia experienced severe wind and storm surge damage with some near-historic levels of coastal flooding. A state of emergency was declared in four states from Florida north to Virginia and in Puerto Rico and the U.S. Virgin Islands, and, for the first time ever, Atlanta was placed under a tropical storm warning.[105,106,107,108] In Florida, a record 6.8 million people were ordered to evacuate, as were 540,000 coastal residents in Georgia and untold numbers in other coastal locations.[102,109,110] Nearly 192,000 evacuees were housed in approximately 700 emergency shelters in Florida alone.[109] According to NOAA's National Centers for Environmental Information (NCEI),[84] Irma significantly damaged 65% of the buildings in the Keys and destroyed 25% of them.

Warm Waters Contribute to the Formation of Hurricane Irma

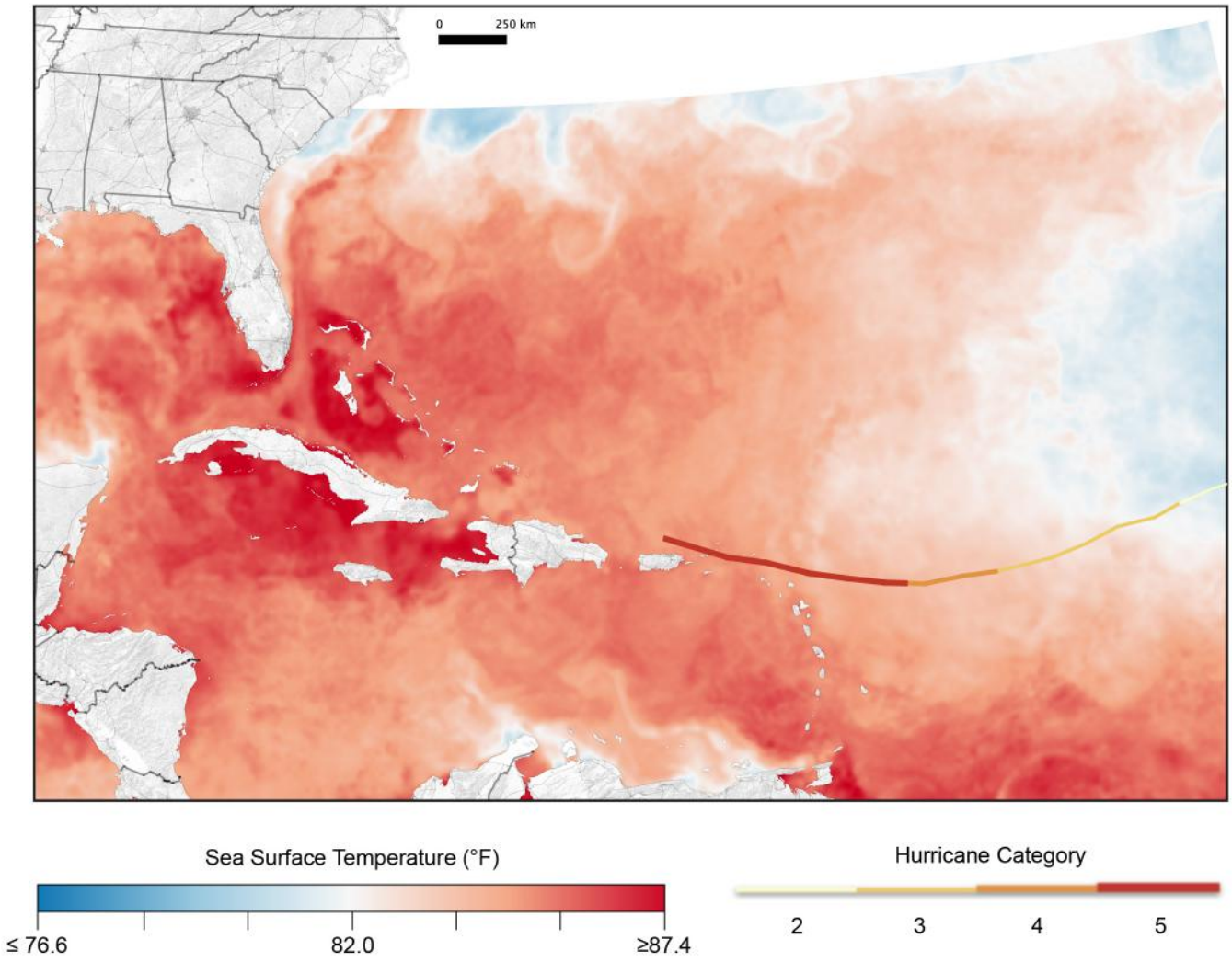


Figure 19.14: Two factors supported Hurricane Irma's strength as it reached the Southeast region: the very warm waters it passed over, depicted in this figure, and the light winds Irma encountered in the upper atmosphere.[101] High-intensity hurricanes such as Irma are expected to become more common in the future due to climate change.[103] Source: NASA 2017.[102]

High rainfall totals were experienced in many impacted areas, with Fort Pierce, Florida, receiving the highest rainfall of more than 21.5 inches[100] and the Florida Keys receiving 12 inches of rain.[84,102] Flooding occurred on most rivers in northern Florida and in many rivers in both Georgia and South Carolina to the point that rescues were required. In Jacksonville, Florida, heavy rains were the major issue causing rivers to reach major or record flood stage and flooded some city streets up to 5 feet deep in water. The heavy rainfall was noted even in Alabama, at 5 inches, and near 6 inches in the mountains of western North Carolina.[100] Twenty-five tornadoes were confirmed from Hurricane Irma, and many of them occurred along the east coast of central and northern Florida.[100] Even as Irma headed north, continuing to lose force, there were still 6.7 million people without electricity.[109]

According to NCEI,[84] the U.S. direct cost from Hurricane Irma is approximately $50 billion (in 2017 dollars), and the non-U.S. territory Caribbean Islands could add another $10–$15 billion to that total. Of the $50 billion, approximately $30–$35 billion accounts for wind and flood damage to a combination of residential and commercial properties, automobiles, and boats—with 80%–90% of this cost felt in Florida. The remainder of the costs include $5 billion for infrastructure repairs and $1.5–$2.0 billion for damage to the agricultural sector, also mainly in Florida. The remaining costs would address losses in the U.S. Virgin Islands and Puerto Rico.[84] The losses could have been worse except for the fact that Florida has implemented one of the strictest building codes in the country after the destruction caused by Hurricane Andrew in 1992.[111] Recent estimates using insured loss data show that implementing the Florida Building Code resulted in a 72% reduction of windstorm losses, and for every $1 in added cost to implement the building code, there is a savings of $6 in reduced losses, with the return or payback period being roughly 8 years (in 2010 dollars).[111]

Indirect impacts and costs are difficult to calculate and would add to the totals. In Central and South Florida, such things would include the closing of schools, colleges, and universities; the closing of tourist attractions and the cancellation of thousands of flights into and out of region; and the closing or restricting of the use of seaports including Canaveral, Key West, Miami, and Jacksonville, among others.[109,112] The Select Committee on Hurricane Response and Preparedness: Final Report[109] estimates that there were 84 U.S. deaths attributable to Hurricane Irma and other untold damage and human suffering. While the hurricane directly damaged portions of the Southeast, the impacts could be felt around the country in the form of business interruptions (such as tourism), transportation and infrastructure damages (such as ports, roadways, and airports), increases in fuel costs, and $2.5 billion (in 2018 dollars) in total estimated crop losses,[109] which had the potential to impact the cost of food and other products for all Americans.

Key Message 3

Natural Ecosystems Will Be Transformed

The Southeast's diverse natural systems, which provide many benefits to society, will be transformed by climate change. Changing winter temperature extremes, wildfire patterns, sea levels, hurricanes, floods, droughts, and warming ocean temperatures are expected to redistribute species and greatly modify ecosystems. As a result, the ecological resources that people depend on for livelihood, protection, and well-being are increasingly at risk, and future generations can expect to experience and interact with natural systems that are much different than those that we see today.

Ecosystems in the Southeast span the transition zone between tropical and temperate climates. The region's more temperate ecosystems include hardwood forests, spruce-fir forests, pine-dominated forests, and salt marshes. The region's more tropical ecosystems include mangrove forests, coral reefs, pine savannas, and the tropical freshwater wetlands of the Everglades. Ecological diversity in the Southeast is high,[113,114,115,116,117] and southeastern ecosystems and landscapes provide many benefits to society. In addition to providing habitat for fish and wildlife species, ecosystems in the Southeast provide recreational opportunities, improve water quality, provide seafood, reduce erosion, provide timber, support food webs, minimize flooding impacts, and support high rates of carbon sequestration (or storage).[118,119,120] These ecological resources that people depend on for livelihoods, protection, and well-being are increasingly at risk from the impacts of climate change.

Climate greatly influences the structure and functioning of all natural systems (Ch. 7: Ecosystems). An analysis of ecological changes that have occurred in the past can help provide some context for anticipating and preparing for future ecological changes. In response to past climatic changes, many ecosystems in the Southeast were much different than those present today. For example, since the end of the last glacial maximum (about 19,000 years ago—the most recent period of maximum ice extent),[121] forests in the region have been transformed by warming temperatures, sea level rise, and glacial retreat.[122,123] Spruce species that were once present in the region's forests have moved northward and have been replaced by oaks and other less cold-tolerant tree species that have expanded from the south.[124] And along the coast, freeze-sensitive mangrove forests and other tropical coastal species have been expanding northward and upslope since the last glacial maximum.[125,126,127,128,129]

In the coming decades and centuries, climate change will continue to transform many ecosystems throughout the Southeast,[6,130,131,132,133,134,135] which would affect many of the societal benefits these ecosystems provide. As a result, future generations can expect to experience, interact with, and potentially benefit from natural systems that are much different than those that we see today (Ch. 7: Ecosystems).[136,137]

Warming Winter Temperature Extremes

Changes in winter air temperature patterns are one aspect of climate change that will play an especially important role in the Southeast. By the late 21st century under the higher scenario (RCP8.5), the freeze-free season is expected to lengthen by more than a month. Winter air temperature extremes (for example, freezing and chilling events) constrain the northern limit of many tropical and subtropical species.[138,139,140,141,142,143,144] Certain ecosystems in the region are located near thresholds where small changes in winter air temperature regimes can trigger comparatively large and abrupt landscape-scale ecological changes (in other words, ecological regime shifts).[135,145] Reductions in the frequency and intensity of cold winter air temperature extremes can allow tropical and subtropical species to move northward and replace more temperate species. Where climatic thresholds are crossed, certain ecosystem and landscapes will be transformed by changing winter air temperatures.

Plant hardiness zone maps help convey the importance of winter air temperature extremes for species and natural systems in the Southeast. To help gardeners and farmers, the U.S. Department of Agriculture has produced plant hardiness zone maps that can be used to determine which species are most likely to survive and thrive in a given location. The plant hardiness zones are reflective of the frequency and intensity of winter air temperature

extremes in a specific region. Already, in response to climate change, plant hardiness zones in certain areas are moving northward and are expected to continue their northward and upslope progression.[139,142,146,147] Continued reductions in the frequency and intensity of winter air temperature extremes are expected to change which species are able to survive and thrive in a given location (Figure 19.15). For example, citrus species are sensitive to freezing and chilling temperatures.[148] However, in the future, climate change is expected to enable the survival of citrus in areas that are north of the current tolerance zone.[142]

The effects of changing winters reach far beyond just agricultural and garden plants. Along the coast, for example, warmer winter temperatures are expected to allow mangrove forests to move northward and replace salt marshes (Figures 19.16 and 19.17).[135,149,150,151,152] Coastal wetlands, like mangrove forests and salt marshes, are abundant in the Southeast.[153,154] The societal benefits provided by coastal wetlands are numerous.[119] Hence, where coastal wetlands are abundant (for example, the Mississippi River Delta), their cumulative value can be worth billions of dollars each year and trillions of dollars over a 100-year period.[155] Coastal wetlands provide seafood, improve water quality, provide recreational opportunities, reduce erosion, support food webs, minimize flooding impacts, and support high rates of carbon sequestration.[118] Foundation species are species that create habitat and support entire ecological communities.[156,157] In coastal wetlands and many other ecosystems, foundation plant species play an especially important role. Hence, the loss and/or replacement of foundation plant species, like salt marsh grasses, will have ecological and societal consequences in certain areas.[135,145,157,158,159,160,161,162,163,164]

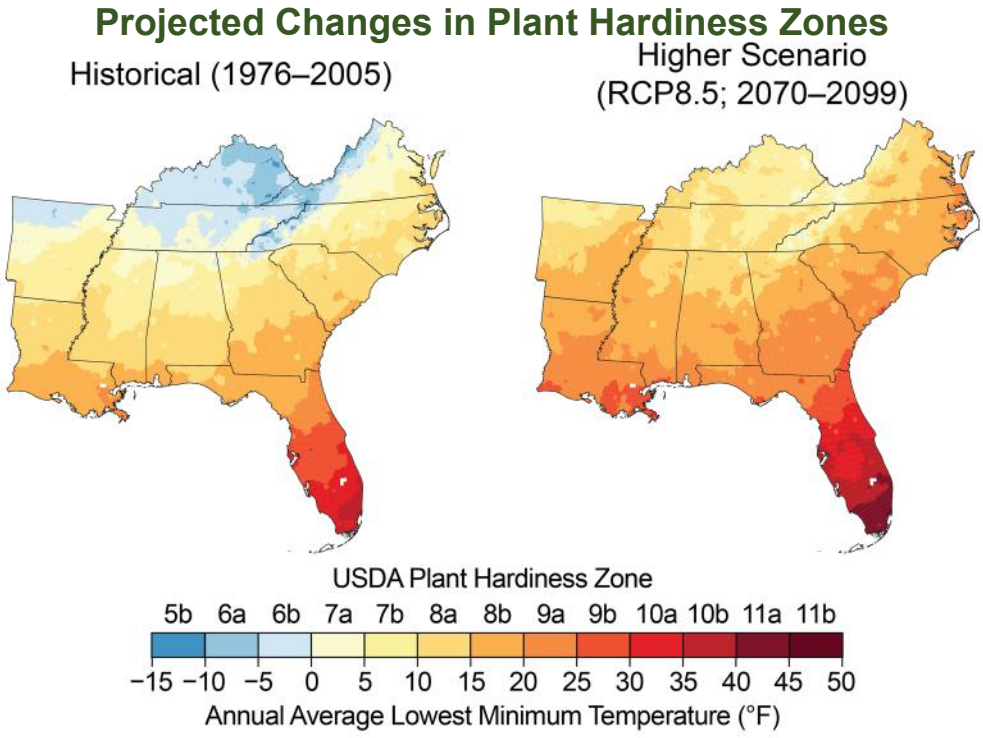


Figure 19.15: Increasing winter temperatures are expected to result in a northward shift of the zones conducive to growing various types of plants, known as plant hardiness zones. These maps show the mean projected changes in the plant hardiness zones, as defined by the U.S. Department of Agriculture (USDA), by the late 21st century (2070–2099) under a higher scenario (RCP8.5). The USDA plant hardiness zones are based on the average lowest minimum temperature for the year, divided into increments of 5°F. Based on these projected changes, freeze-sensitive plants, like oranges, papayas, and mangoes, would be able to survive in new areas.[142] Note that large changes are projected across the region, but especially in Kentucky, Tennessee, and northern Arkansas. Sources: NOAA NCEI and CICS-NC.

While salt marsh and mangrove wetlands both contain valuable foundation species, some of the habitat and societal benefits provided by existing salt marsh habitats will be affected by the northward expansion of mangrove forests.[145,158,160,161,164,165]

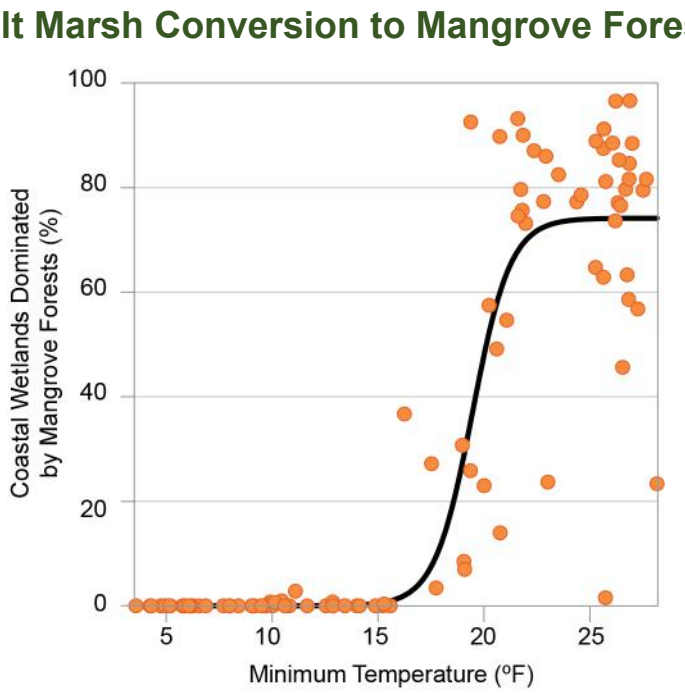


Figure 19.16: Where tropical and temperate ecosystems meet, warmer winter temperatures can lead to large ecological changes such as mangrove forest replacement of salt marshes along the Gulf and Atlantic Coasts. Mangrove forests are sensitive to freezing temperatures and are expected to expand northward at the expense of salt marshes. The figure shows the relationship between temperature and the percentage area dominated by mangrove forests. Mangrove expansion would entail a grassland-to-forest conversion, which would affect fish and wildlife habitat and many societal benefits. Source: adapted from Osland et al. 2013.[135] ©2012 Blackwell Publishing Ltd.

Transitioning Coastal Ecosystems

Figure 19.17: In Louisiana and parts of northern Florida, future coastal wetlands are expected to look and function more like the mangrove-dominated systems currently present in South Florida and the Caribbean. Like salt marshes (left), mangrove forests (right) provide coastal protection against wind and waves (Ch. 20: U.S. Caribbean, KM 2). Photo credit: Michael Osland.

In addition to plants, warmer winter air temperatures will also affect the movement and interactions between many different kinds of organisms. For example, certain insect species, including mosquitoes and tree-damaging beetles, are expected to move northward in response to climate change, which could affect human health and timber supplies.[30,144,166,167,168,169,170,171,172] And some bird species, including certain ducks, are not expected to migrate as far south in response to milder winters,[173] which could affect birding and hunting recreational opportunities. Many recreational fishery populations in tropical coastal areas are freeze-sensitive[138,174,175,176,177,178] and are, therefore, expected to move northward in response to warmer water and air temperatures. Although the appearance of tropical recreational fish, like snook for example, may be favorable for some anglers, the movement of tropical marine species is expected to greatly modify existing food webs and ecosystems (Ch. 7: Ecosystems, Figure 7.4).[179] Some problematic invasive species are expected to be favored by changing winters. For example, in South Florida, the Burmese python and the Brazilian pepper tree are two freeze-sensitive, nonnative species that have, respectively, decimated mammal populations and transformed native plant communities within Everglades National Park.[180,181,182,183,184,185,186,187,188] In the future, warmer winter temperatures are expected to facilitate the northward movement of these problematic invasive species, which would transform natural systems north of their current distribution.

Warm Winters Favor Invasive Species

Figure 19.18: Burmese pythons are apex predators (not preyed upon by other animals) that are sensitive to cold temperatures and are expected to be favored by warming winters. This photo is from Everglades National Park, where unintentionally introduced pythons have expanded and reduced native mammal populations. Photo credit: U.S. Geological Survey.

Changing Patterns of Fire

In the Southeast region, changing fire regimes (defined by factors including frequency, intensity, size, pattern, season, and severity) are expected to have a large impact on natural systems. Fire has historically played an important role in the region, and ecological diversity in many southeastern natural systems is dependent upon fire.[115,116,134,189] Although the total area burned by wildfire is greatest in the western United States, the Southeast has the largest area burned by prescribed fire (see Case Study "Prescribed Fire") and the highest number of wildfires.[134,190] In the future, rising temperatures and increases in the duration and intensity of drought are expected to increase wildfire occurrence and also reduce the effectiveness of prescribed fire.[3,4,5,6] Moreover, rapid urban expansion near managed forests has the potential to reduce opportunities to use prescribed fire, which could lead to native species declines, increased wildfire occurrence, and economic and health impacts.[134,191]

A recent example of the importance of fire lies in the forests of the southern Appalachians. Over the last century, invasive insects, logging, and pathogens have transformed forests in the region.[192] Warmer temperatures and insects have led to the loss of cold-adapted boreal communities, and flammable, fire-adapted tree species have been replaced by less flammable, fire-sensitive species—a process known as mesophication.[193,194] However, intense fires, like those observed in 2016, can halt the mesophication process. High temperatures, increases in accumulated plant material on the forest floor, and a four-month seasonal drought in the fall of 2016 collectively produced the worst wildfires the region has seen in a century. Intra-annual droughts, like the one in 2016, are expected to become more frequent in the future.[6] Thus, drought and greater fire activity[134] are expected to continue to transform forest ecosystems in the region (see Ch. 6: Forests, KM 1).

Case Study: Prescribed Fire

With wildfire projected to increase in the Southeast,[6,191] prescribed fire (the purposeful ignition of low-intensity fires in a controlled setting), remains the most effective tool for reducing wildfire risk.[4,195] Department of Defense (DoD) lands represent the largest reservoirs of biodiversity and native ecosystems in the region.[117] Military activities are a frequent source of wildfires, but increases in prescribed fire acres (Figure 19.19) show a corresponding decrease in wildfire ignitions for DoD.[4] Climate resilience by DoD is further achieved through restoration of native longleaf pine forests that occupy a wide range of site types, including wetland and well-drained soils—the latter leading many to characterize this forest as being drought resistant.[196,197,198,199] In addition to proactive adaptation through prescribed fire, DoD has been a leader in climate strategies that include regional conservation planning, ecosystem management, endangered species recovery, and research funding.

Wildlife and Prescribed Fire

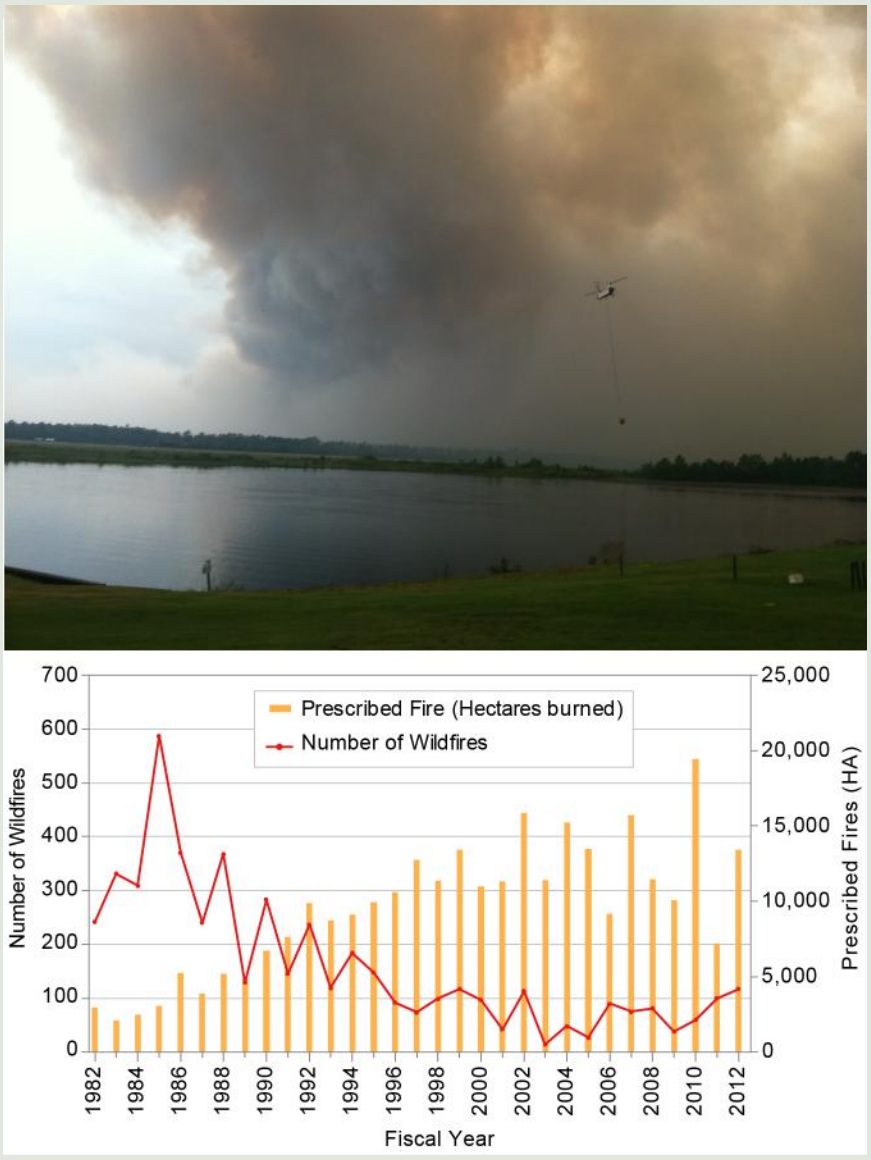


Figure 19.19: (top) A helicopter drops water on a 1,500-hectare wildfire on Hurlburt Field (Eglin Air Force Base) in Florida in June of 2012. (bottom) The increased use of prescribed fire at Ft. Benning, Georgia, led to a decrease in wildfire occurrence from 1982 to 2012. Photo credit: Kevin Hiers, Tall Timbers. Figure source: adapted from Addington et al. 2015.[4] Reprinted by permission of CSIRO Australia, ©CSIRO.

Rising Sea Levels and Hurricanes

Rising sea levels and potential changes in hurricane intensity are aspects of climate change that are expected to have a tremendous effect on coastal ecosystems in the Southeast (Ch. 8: Coastal, KM 2; Ch. 9: Oceans, KM 1). Since coastal terrestrial and freshwater ecosystems are highly sensitive to increases in inundation and salinity, sea level rise will result in the rapid conversion of these systems to tidal saline habitats. Historically, coastal ecosystems in the region have adjusted to sea level rise by vertical and horizontal movement across the landscape.[125,129,200,201] As sea levels rise in the future, some coastal ecosystems will be submerged and converted to open water, and saltwater intrusion will allow salt-tolerant coastal ecosystems to move inland at the expense of upslope and upriver ecosystems.[128,202,203,204,205,206,207,208] Where barriers are present (for example, levees and other coastal infrastructure), the potential for landward migration of natural systems will be reduced and certain coastal habitats will be lost (Ch. 20: U.S. Caribbean, KM 3).[204] With higher sea levels and increasing saltwater intrusion, the high winds, high precipitation rates, storm surges, and salts that accompany hurricanes will have large ecological impacts to terrestrial and freshwater ecosystems.[209,210]

An example of the effects of rising sea levels can be found in Louisiana, which faces some of the highest land loss rates in the world. The ecosystems of the Mississippi River Delta provide at least $12–$47 billion (in 2017 dollars) in benefits to people each year.[155] These benefits include hurricane storm protection, water supply, furs, habitat, climate stability, and waste treatment. However, between 1932 and 2016, Louisiana lost 2,006 square miles of land area (see Case Study "A Lesson Learned for Community Resettlement"),[211] due in part to high rates of relative sea level rise.[212,213,214,215] The rate of wetland loss during this period equates to Louisiana losing an area the size of one football field every 34 to 100 minutes.[211] To protect and restore the Louisiana coast, the Louisiana Coastal Protection and Restoration Authority (CPRA) has worked with local, state, and federal partners to iteratively develop a 2017 Coastal Master Plan that identifies investments that can provide direct restoration and risk reduction benefits.[216] The aim of the 50-year, $50-billion strategy is to sustain Louisiana's coastal ecosystems, safeguard coastal populations, and protect vital economic and cultural resources.[216]

Drought and Extreme Rainfall

Climate change is expected to intensify the hydrologic cycle and increase the frequency and severity of extreme events like drought and heavy rainfall. Drought and extreme heat can result in tree mortality and transform the region's forested ecosystems (Ch. 6: Forests, KM 1).[217,218,219,220,221,222,223] Drought can also affect aquatic and wetland ecosystems,[224] for example by contributing to mortality and ecological transformations in salt marshes,[225,226] mangrove forests,[227,228,229,230,231] and tidal freshwater forests.[232] In addition to drought, extreme rainfall events are also expected to become more frequent and severe in the future. The prolonged inundation and lack of oxygen that results from extreme rainfall can also result in mortality, such as the dieback of critical foundation plant species, and other large impacts to natural systems.[233] In combination, future increases in the frequency and severity of both extreme drought and extreme rainfall are expected to transform many ecosystems in the Southeast region. Natural systems in the region will have to become resistant and resilient to both too little water and too much water. The ecological transformations induced by these extreme events will affect many of the benefits that natural systems provide to society.

Warming Ocean Temperatures

Warming ocean temperatures due to climate change are expected to have a large effect on marine and coastal ecosystems (Ch. 9: Oceans, KM 3).[234,235,236] Many species are sensitive to small changes in ocean temperature; hence, the distribution and abundance of marine organisms are expected to be greatly altered by increasing ocean temperatures. For example, the distribution of tropical herbivorous fish has been expanding in response to warmer waters, which has resulted in the tropicalization of some temperate marine ecosystems and decreases in the cover of valuable macroalgal plant communities.[179] A decrease in the growth of sea turtles in the West Atlantic has been linked to higher ocean temperatures.[237] Due to climate change, warming ocean temperatures in the coming decades are expected to transform many marine and coastal ecosystems across the Southeast. However, the impacts to coral reef ecosystems in the region have been and are expected to be particularly dire. Coral reefs are biologically diverse ecosystems that provide many societal benefits, including coastal protection from waves, habitat for fish, and recreational and tourism opportunities.[238,239] However, coral reef mortality in the Florida Keys and across the globe has been very high in recent decades, due in part to warming ocean temperatures, nutrient enrichment, overfishing, and coastal development.[240,241,242,243,244] Small increases in ocean temperature can cause corals to expel the symbiotic algae upon which they depend for nourishment. When this happens, corals lose their color and die in a process known as coral bleaching (Ch. 9: Oceans, KM 1). Coral elevation and volume in the Florida Keys have been declining in recent decades,[245] and present-day temperatures in the region are already close to bleaching thresholds; hence, it is likely that many of the remaining coral reefs in the Southeast region will be lost in the coming decades.[246,247] In addition to warming temperatures, accelerated ocean acidification is also expected to contribute to coral reef mortality and decline.[248,249] When coral reefs are lost, coastal communities lose the many benefits provided by these valuable ecosystems, including lost tourism opportunities, a decline in fisheries, and a decrease in wave protection.[246,247]

Key Message 4

Economic and Health Risks for Rural Communities

Rural communities are integral to the Southeast's cultural heritage and to the strong agricultural and forest products industries across the region. More frequent extreme heat episodes and changing seasonal climates are projected to increase exposure-linked health impacts and economic vulnerabilities in the agricultural, timber, and manufacturing sectors. By the end of the century, over one-half billion labor hours could be lost from extreme heat-related impacts. Such changes would negatively impact the region's labor-intensive agricultural industry and compound existing social stresses in rural areas related to limited local community capabilities and associated with rural demography, occupations, earnings, literacy, and poverty incidence. Reduction of existing stresses can increase resilience.

In the Southeast, over 56% of land remains rural (nonmetropolitan) and home to approximately 16 million people, or about 17% percent of the region's population.[250] These rural areas are important to the social and economic well-being of the Southeast. Many in rural communities are maintaining connections to traditional livelihoods and relying on natural

resources that are inherently vulnerable to climate change. The Southeast has the second highest number of farmworkers hired per year compared to other National Climate Assessment (NCA) regions.[251] Climate trends and possible climate futures show patterns that are already impacting—and are expected to further impact—rural sectors, from agriculture and forestry to human health and labor productivity (Ch. 10: Ag & Rural, KM 3). For example, shrimping, oystering, and fishing along the coast are long-standing traditions in the coastal economy that are expected to face substantial challenges. For example, by the end of the century, annual oyster harvests in the Southeast are projected to decline between 20% (19%–22%) under a lower scenario (RCP4.5) and 46% (44%–48%) under a higher scenario (RCP8.5), leading to projected price increases of 48% (RCP4.5) to 140% (RCP8.5).[35] Projected warming ocean temperatures, sea level rise, and ocean and coastal acidification are raising concern over future harvests (Ch. 9: Oceans, KM 2).[35,252] While adaptation and resilience can moderate climate change impacts, rural areas generally face other stressors, such as poverty and limited access to healthcare, which will make coping to these climate-related challenges more difficult.

Heat-related stresses are presently a major concern in the Southeast. Future temperature increases are projected to pose challenges for human health. While recent regional temperature trends have not shown the same consistent rate of daytime maximum temperature increase as observed in other parts of the United States, climate model simulations strongly suggest that daytime maximum temperatures are likely to increase as humans continue to emit greenhouse gases into the atmosphere.[13] The resulting temperature increases are expected to add to the heat health burden in rural, as well as urban, areas.[35] Projected temperature increases also pose challenges for crop production dependent on periods of lower temperatures to reach full productivity. Drought has been a recurrent issue in the Southeast affecting agriculture, forestry, and water resources.[253] With rapid growth in population and overall demand, drought is increasingly a concern for water resource management sectors such as cities, ecosystems, and energy production.

Diverse Rural Regions

Urban and rural areas exist along a continuum from major metro areas to suburbs, small towns, and lightly populated places. These areas are linked through many processes, commuting patterns, and shared central services, such as airports and hospitals, that connect the risks. Rapid population growth with associated urbanization and suburbanization over the last several decades has resulted in a more fine-grained forest landscape with smaller and more numerous forest patches.[254] Agriculture, manufacturing, tourism, and other major economic sectors are spread across the Southeast region. Rural counties in the region generally have a diversified economy with a relatively low percentage being heavily dependent on one sector. While well known for agriculture and forestry, rural areas also support manufacturing and tourism.[250]

In 2013, approximately 34% of the U.S. manufacturing output, or about $700 billion (dollar year not reported), came from the Southeast and Texas, including rural areas.[255] While manufacturing growth has been particularly strong in the Southeast in recent years, future climate changes would pose challenges for economic competitiveness. For companies involved in food processing, there are additional secondary economic risks associated with climate impacts on crops and livestock that could alter price or availability.[64,255] Facilities that are energy- or water-intensive are more likely to face increases in the costs and

decreases in the availability of these resources, with potential impacts to their economic competitiveness.[246,255]

Energy production, and its dependence on water availability, is a key concern in the Southeast, given the region's growing population and large, diversified economy. An increasing number of high heat and dry days as the climate warms poses a risk to efficient power generation, particularly under conditions where the mode of primary generation moves towards natural gas and water-intensive nuclear power.[256]

Risks to Agriculture and Forestry

Agriculture, livestock rearing, and forestry activities are widespread and varied through the Southeast region.[7] Climate change is expected to have an overall negative impact on agricultural productivity in the United States,[35] although some crops could also become newly viable alternatives (Key Message 3, Figure 19.15). Increases in temperatures, water stress, freeze-free days, drought, and wildfire risks, together with changing conditions for invasive species and the movement of diseases, create a number of potential risks for existing agricultural systems (Ch. 10: Ag & Rural, KM 1).[7] In particular, precipitation trends for the Southeast region show an inclination towards slightly drier summers, which could reduce productivity, and wetter fall seasons, which can make it difficult to harvest the full crop. Multimodel averages of climate model simulations (CMIP3 [SRES A2] and CMIP5 [RCP8.5] higher scenarios) show that there is a greater risk of drier summers by the middle of the century in the western portion of the Southeast and in southern Florida, while wetter fall seasons are more likely in the eastern portion of the region.[257]

The conditions for raising and harvesting crops and livestock are projected to change. Higher temperatures can result in decreasing productivity of some cultivated crops, including cotton, corn, soybeans, and rice.[7] Livestock, which includes hogs and pigs, horses, ponies, mules, burros, and donkeys as well as poultry and processed poultry for consumption (for example, chicken nuggets), is a large component of the agricultural sector for these states and the Nation.[258] Livestock are all vulnerable to heat stress, and their care under projected future conditions would require new or enhanced adaptive strategies (Ch. 10: Ag & Rural, KM 3).

Recent changes in seasonal temperatures that are critical for plant development will continue to impact regionally important crops. Plants collected from the wild may become less available as the ideal conditions for their growth shift to other areas (see Case Study "Mountain Ramps"). Peaches—an important crop in the Southeast—require an adequate period of cool temperatures, called the chill period, to produce yields that are economically viable. Peaches also require warm temperatures at specific times during their development.[259] If the warm temperatures come too early, the chill periods could be too short or the peach blossoms can flower too soon and be in danger of late freeze impacts. A late freeze in March 2017 caused over a billion dollars of damages to peaches and other fruit crops.[84] To assist peach growers in adapting to such changes, researchers are working to develop peach varieties that can produce quality fruits in warmer winters and are developing winter chill models that can assist in adaptation planning efforts.[260,261]

Forests, both natural and plantation, in the Southeast are vulnerable to climate variability and change. Southeastern forests represent almost 27% of the U.S. total[262] and are the highest-valued crop in the region.[7] The vast majority of forest is held in private hands, primarily corporate. Forest cover ranges from almost 50% to 80% in these states, creating

large areas of interface between populations and forests.[262] Jobs in timber, logging, and support for agriculture and forestry totaled approximately 458,000.[263] (See Ch. 6: Forests, KM 3 for additional discussion on forest change impacts on rural landscapes.)

The Southeast is one of the most dynamic regions for forest change on the globe,[269] though much of the change owes to intensive rotations of pine production and economic forces that drive frequent conversion between forest and agricultural uses in rural areas.[270,271] Climate is expected to have an impact on the region's forests primarily through changes in moisture regimes.[272] Species migration westward across the eastern United States in response to changing precipitation patterns has already been noted.[273] Drought is likely to alter fire regimes and further interact with species distributions (see Key Message 3). The interactions of altered precipitation and natural disturbances will be important in understanding impacts to the forests not dominated by industrial forestry (Ch. 6: Forests, KM 1 and KM 3).[274]

Wildfire is a well-known risk in the Southeast region, where it occurs with greater frequency than any other U.S. region.[275] However, mitigation strategies, particularly the use of prescribed fire, can significantly reduce wildfire risk and have been widely adopted across rural communities in the Southeast.[190] A doubling of prescribed fire at the landscape scale has been found to reduce wildfire ignitions by a factor of four,[4] while it is well documented that prescribed fire reduces the potential for crown fire in treated forest stands.[276] With greater projected fire risks,[191,277] more attention on how to foster fire-adapted communities offers opportunities for risk reduction (see Case Study "Prescribed Fire" and Key Message 3).[278,279]

Case Study: Mountain Ramps

The Cherokee have been harvesting ramps, a wild onion (*Allium tricoccum*), in the southern Appalachians, their ancestral homelands, for thousands of years.[264,265] Collecting ramps for food sustenance is only one aspect of this cultural tradition. The family-bound harvesting techniques are equally as important and make up part of the deeply held tribal lifeways (Ch. 15: Tribes, KM 2). Ramps emerge in springtime and provide important nutrients after a long winter with a dearth of fresh vegetables. These plants grow in moist forest understory areas that are sensitive to temperature and soil moisture.[266]

Figure 19.20: This up-close image of a ramp (*Allium tricoccum*), harvested from the wild, shows leaves and the bulb/corm of the plant. Photo credit: Gary Kaufman, USDA Forest Service Southern Research Station.

In the southern Appalachians, ramps are threatened by two major processes: overharvesting pressures and a changing climate that could expose these plants to higher temperatures and lower soil moisture conditions during sensitive growth periods (Ch. 10: Ag & Rural, KM 1).[267,268] Although ramps are found all along the Appalachian mountain range, on Cherokee ancestral lands, they are already in their southernmost range. Climate change thus acts to increase the vulnerability of this plant to the existing stressors.

Heat, Health, and Livelihoods

Heat-related health threats are already a risk in outdoor jobs and activities. While heat illness is more often associated with urban settings, rural populations are also at risk. For example, higher rates of heat-related illness have been reported in rural North Carolina compared to urban locations.[280] However, strategies to reduce health impacts on hot days, such as staying indoors or altering times outdoors, are already contributing to reducing heat-related illness in the Southeast.[281]

Workers in the agriculture, forestry, hunting, and fishing sectors together with construction and support, waste, and remediation services work are the most highly vulnerable to heat-related deaths in the United States, representing almost 68% of heat-related deaths nationally.[282] Six of the ten states with the highest occupational heat-related deaths in these sectors are in the Southeast region, accounting for 28.6% of occupational heat-related deaths between 2000 and 2010.[282] By 2090, under a higher scenario (RCP8.5), the Southeast is projected to have the largest heat-related impacts on labor productivity in the country, resulting in average annual losses of 570 million labor hours, or $47 billion (in 2015 dollars, undiscounted), a cost representing a third of total national projected losses, although these figures do not include adaptations by workers or industries (Figure 19.21).[35]

Investing in increased cooling is one likely form of adaptation. Among U.S. regions, the Southeast is projected to experience the highest costs associated with meeting increased electricity demands in a warmer world.[35]

Compounding Stresses and Constraints to Adaptation

The people of the rural Southeast confront a number of social stresses likely to add to the challenges posed by increases in climate stresses.[283] Rural communities tend to be more vulnerable due to factors such as demography, occupations, earnings, literacy, poverty incidence, and community capacities (Ch. 10: Ag & Rural, KM 4).[8,9,10] Reducing stress associated with these factors can increase household and community resilience.[9,284]

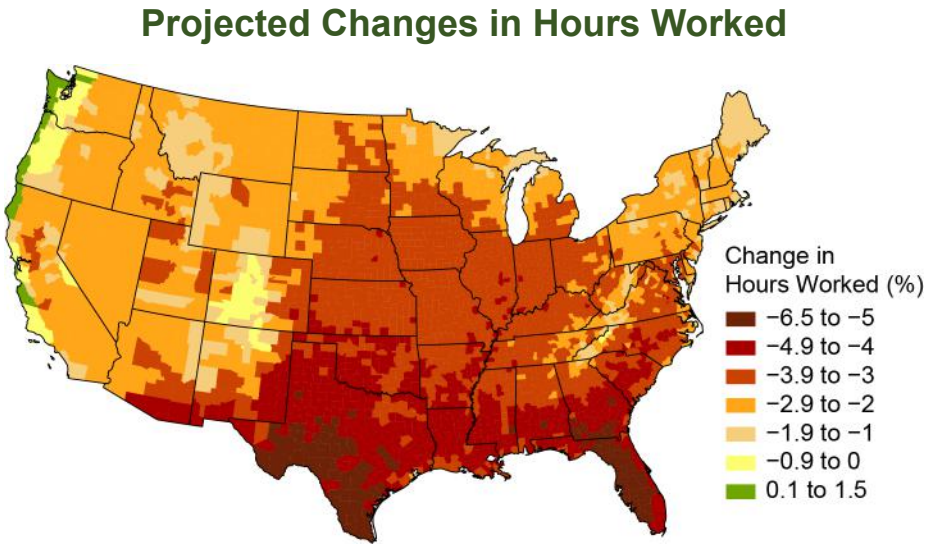


Figure 19.21: This map shows the estimated percent change in hours worked in 2090 under a higher scenario (RCP8.5). Projections indicate an annual average of 570 million labor hours lost per year in the Southeast by 2090 (with models ranging from 340 million to 820 million labor hours).[35] Estimates represent a change in hours worked as compared to a 2003–2007 average baseline for high-risk industries only. These industries are defined as agriculture, forestry, and fishing; hunting, mining, and construction; manufacturing, transportation, and utilities. Source: adapted from EPA 2017.[35]

Persistent rural poverty stands out in the Southeast (Figure 19.22). The rural counties in the region are experiencing higher levels of population loss (13% of rural counties lost population) and low educational attainment (38% of rural counties), with 35% of rural counties experiencing poverty rates of more than 20% persisting over approximately 30 years.[10] The Southeast is expected to experience the highest costs associated with meeting increased energy demands; an estimated $3.3 billion each year under a higher scenario (RCP8.5) and $1.2 billion annually under a lower scenario (RCP4.5) by the end of the century.[35] Energy poverty is a situation "where individuals or households are not able to adequately heat or provide other required energy services in their homes at affordable cost."[285] A case study from rural eastern North Carolina further explains energy poverty as a function of the energy efficiency of the home, energy provision infrastructure, physical health, low incomes, and support of social networks, which collectively influence households' choices about the amount of heating and cooling they can afford.[286] The National Weather Service (NWS) calculates degree days,[287] a way of tracking energy use. NWS starts with the assumption that when the average outside temperature is 65°F, heating or cooling is not needed in order to be comfortable. The difference between the average daily temperature and 65°F is the number of cooling or heating degrees for that day. These days can be added up over time—a month or a year—to give a combined estimate of energy needed for heating or cooling. Although heating costs are expected to decrease as the climate warms in the Southeast, the number of cooling degree days is expected to increase and the length of the cooling season expected to expand, increasing energy demand and exacerbating rural energy poverty (Figure 19.22).

The ability to cope with current and potential impacts, such as flooding, is further reduced by limited county resources. A study of hazard management plans (2004–2008) in 84 selected rural southeastern counties found these plans scored low across various criteria.[288] The rural, geographically remote locations contributed to more difficult logistics in reaching people. Interviewees also identified low-income and minority communities, substandard housing, lack of access to vehicles for evacuation, limited modes of communication, and limited local government capacity as contributing factors to difficulties in emergency planning.[288]

The healthcare system in the Southeast is already overburdened and may be further stressed by climate change. Between 2010 and 2016, more rural hospitals closed in the Southeast than any other region, with Alabama, Georgia, Mississippi, and Tennessee being among the top five states for hospital closures.[289] This strain, when combined with negative health impacts from climate change stressors (such as additional patient demand due to extreme heat and vector-borne diseases and greater flood risk from extreme precipitation events), increases the potential for disruptions of health services in the future. The Green River District Health Department recently did an assessment of ways to reduce vulnerability to negative health impacts of climate change in a mostly rural region of western Kentucky.[290] As a result, the local health department plans to enhance existing epidemiology, public health preparedness, and community health assessment services.[290]

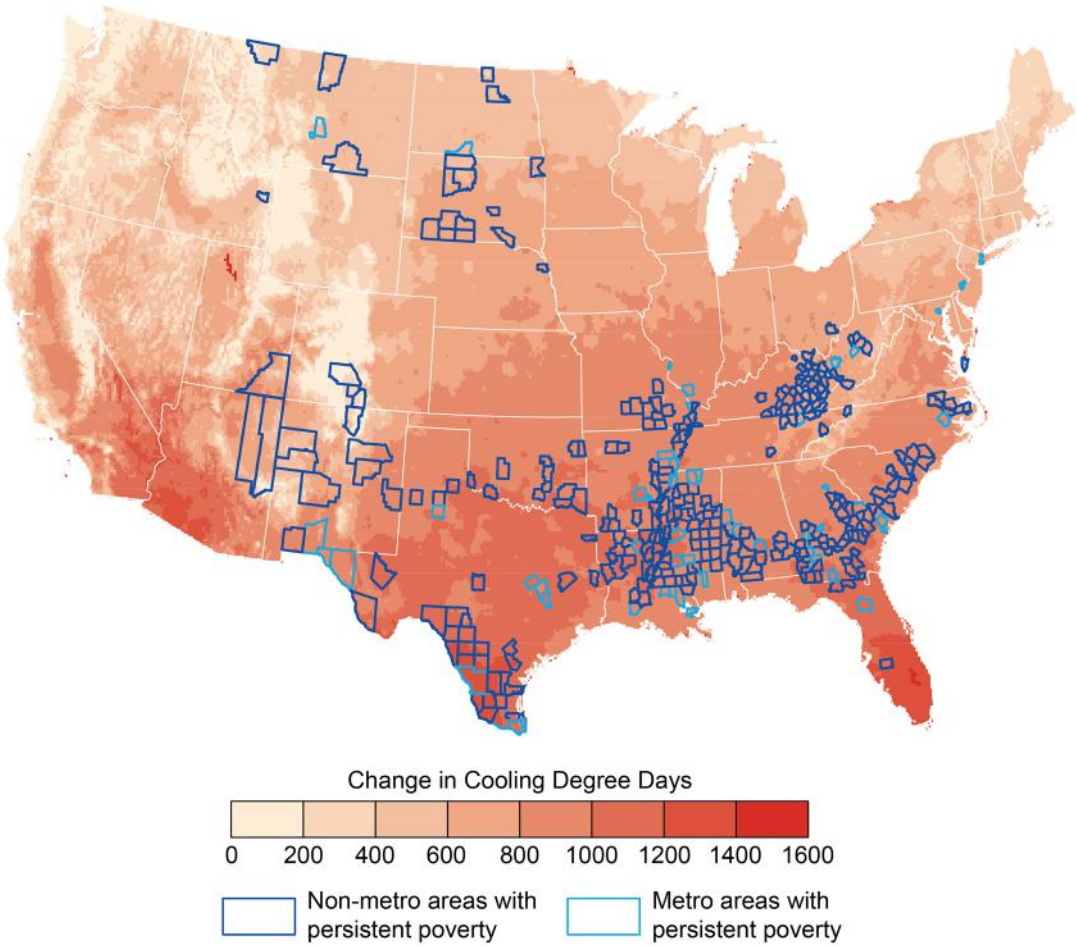


Figure 19.22: The map shows projected changes in cooling degree days by the mid-21st century (2036–2065) under the higher scenario (RCP8.5) based on model simulations. Rural counties experiencing persistent poverty are concentrated in the Southeast, where the need for additional cooling is expected to increase at higher rates than other areas of the country by mid-century. Sources: NOAA NCEI, CICS-NC, and ERT, Inc.

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Opening Image Credit

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Traceable Accounts

Process Description

Prior to identifying critical issues for the Southeast assessment focuses for the Fourth National Climate Assessment (NCA4), the Chapter Lead (CL) contacted numerous professional colleagues representing various geographic areas (e.g., Florida, Louisiana, and South Carolina) for expert opinions on critical climate change related issues impacting the region, with a particular emphasis on emerging issues since the Third National Climate Assessment (NCA3) effort.[77] Following those interviews, the CL concluded that the most pressing climate change issues to focus on for the NCA4 effort were extreme events, flooding (both from rainfall and sea level rise), wildfire, health issues, ecosystems, and adaptation actions. Authors with specific expertise in each of these areas were sought, and a draft outline built around these issues was developed. Further refinement of these focal areas occurred in conjunction with the public Regional Engagement Workshop, held on the campus of North Carolina State University in March 2017 and in six satellite locations across the Southeast region. The participants agreed that the identified issues were important and suggested the inclusion of several other topics, including impacts on coastal and rural areas and people, forests, and agriculture. Based on the subsequent authors' meeting and input from NCA staff, the chapter outline and Key Messages were updated to reflect a risk-based framing in the context of a new set of Key Messages. The depth of discussion for any particular topic and Key Message is dependent on the availability of supporting literature and chapter length limitations.

Key Message 1

Urban Infrastructure and Health Risks

Many southeastern cities are particularly vulnerable to climate change compared to cities in other regions, with expected impacts to infrastructure and human health (*very likely, very high confidence*). The vibrancy and viability of these metropolitan areas, including the people and critical regional resources located in them, are increasingly at risk due to heat, flooding, and vector-borne disease brought about by a changing climate (*likely, high confidence*). Many of these urban areas are rapidly growing and offer opportunities to adopt effective adaptation efforts to prevent future negative impacts of climate change (*very likely, high confidence*).

Description of evidence base

Multiple studies have projected that urban areas, including those in the Southeast, will be adversely affected by climate change in a variety of ways. This includes impacts on infrastructure[41,42,43,291,292,293] and human health.[30,31,38,294] Increases in climate-related impacts have already been observed in some Southeast metropolitan areas (e.g., Habeeb et al. 2015, Tzung-May Fu et al. 2015[12,39]).

Southeastern cities may be more vulnerable than cities in other regions of the United States due to the climate being more conducive to some vector-borne diseases, the presence of multiple large coastal cities at low elevation that are vulnerable to flooding and storms, and a rapidly growing urban and coastal population.[22,295,296]

Many city and county governments, utilities, and other government and service organizations have already begun to plan and prepare for the impacts of climate change (e.g., Gregg et al. 2017; FTA 2013; City of Fayetteville 2017; City of Charleston 2015; City of New Orleans 2015; Tampa Bay Water 2014; EPA 2015; City of Atlanta 2015, 2017; Southeast Florida Regional Climate Change Compact 2017[44,45,46,50,91,246,297,298,299]). A wide variety of adaptation options are available, offering opportunities to improve the climate resilience, quality of life, and economy of urban areas.[77,300,301,302,303,304]

Major uncertainties

Population projections are inherently uncertain over long time periods, and shifts in immigration or migration rates and shifting demographics will influence urban vulnerabilities to climate change. The precise impacts on cities are difficult to project. The scope and scale of adaptation efforts, which are already underway, will affect future vulnerability and risk. Technological developments (such as a potential shift in transportation modes) will also affect the scope and location of risk within cities. Newly emerging pathogens could increase risk of disease in the future, while successful adaptations could reduce public health risk.

Description of confidence and likelihood

There is *very high confidence* that southeastern cities will *likely* be impacted by climate change, especially in the areas of infrastructure and human health.

Key Message 2

Increasing Flood Risks in Coastal and Low-Lying Regions

The Southeast's coastal plain and inland low-lying regions support a rapidly growing population, a tourism economy, critical industries, and important cultural resources that are highly vulnerable to climate change impacts (*very likely, very high confidence*). The combined effects of changing extreme rainfall events and sea level rise are already increasing flood frequencies, which impacts property values and infrastructure viability, particularly in coastal cities. Without significant adaptation measures, these regions are projected to experience daily high tide flooding by the end of the century (*likely, high confidence*).

Description of evidence base

Multiple lines of research have shown that global sea levels have increased in the past and are projected to continue to accelerate in the future due to increased global temperature and that higher local sea level rise rates in the Mid-Atlantic and Gulf Coasts have occurred.[51,52,53,54,55,56,57,59,61,62]

Annual occurrences of high tide flooding have increased, causing several Southeast coastal cities to experience all-time records of occurrences that are posing daily risks.[1,52,58,60,61,63,67,68]

There is scientific consensus that sea level rise will continue to cause increases in high tide flooding in the Southeast as well as impact the frequency and duration of extreme water level events, causing an increase in the vulnerability of coastal populations and property.[1,60,63,67,68]

In the future, coastal flooding is projected to become more serious, disruptive, and costly as the frequency, depth, and inland extent grow with time.[1,2,35,64,65,67,68]

Many analyses have determined that extreme rainfall events have increased in the Southeast, and under higher scenarios, the frequency and intensity of these events are projected to increase.[19,21,88]

Rainfall records have shown that since NCA3, many intense rainfall events (approaching 500-year events) have occurred in the Southeast, with some causing billions of dollars in damage and many deaths.[68,82,84]

The flood events in Baton Rouge, Louisiana, in 2016 and in South Carolina in 2015 provide real examples of how vulnerable inland and coastal communities are to extreme rainfall events.[81,85,86]

The socioeconomic impacts of climate change on the Southeast is a developing research field.[65,71]

Major uncertainties

The amount of confidence associated with the historical rate of global sea level rise is impacted by the sparsity of tide gauge records and historical proxies as well as different statistical approaches for estimating sea level change. The amount of unpredictability in future projected rates of sea level rise is likely caused by a range of future climate scenarios projections and rate of ice sheet mass changes. Flooding events are highly variable in both space and time. Detection and attribution of flood events are difficult due to multiple variables that cause flooding.

Description of confidence and likelihood

There is *high confidence* that flood risks will *very likely* increase in coastal and low-lying regions of the Southeast due to rising sea level and an increase in extreme rainfall events. There is *high confidence* that Southeast coastal cities are already experiencing record numbers of high tide flooding events, and without significant adaptation measures, it is *likely* they will be impacted by daily high tide flooding.

Key Message 3

Natural Ecosystems Will Be Transformed

The Southeast's diverse natural systems, which provide many benefits to society, will be transformed by climate change (*very likely, high confidence*). Changing winter temperature extremes, wildfire patterns, sea levels, hurricanes, floods, droughts, and warming ocean temperatures are expected to redistribute species and greatly modify ecosystems (*very likely, high confidence*). As a result, the ecological resources that people depend on for livelihood, protection, and well-being are increasingly at risk, and future generations can expect to experience and interact with natural systems that are much different than those that we see today (*very likely, high confidence*).

Description of evidence base

Winter temperature extremes, fire regimes, sea levels, hurricanes, rainfall extremes, drought extremes, and warming ocean temperatures greatly influence the distribution, abundance, and performance of species and ecosystems.

Winter air temperature extremes (for example, freezing and chilling events) constrain the northern limit of many tropical and subtropical species.[30,48,127,132,135,138,139,140,141,142,143,144,145,148,149,150,152,166,167,168,169,170,172,173,174,175,176,177,178] In the future, warmer winter temperatures are expected to facilitate the northward movement of cold-sensitive species, often at the expense of cold-tolerant species.[132,135,142,145,149,150,152,166,169,173,179] Certain ecosystems are located near thresholds where small changes in winter air temperature regimes can trigger comparatively large and abrupt landscape-scale ecological changes (i.e., ecological regime shifts).[135,145,152]

Changing fire regimes are expected to have a large impact on natural systems. Fire has historically played an important role in the region, and ecological diversity in many southeastern natural systems is dependent upon fire.[115,116,134,189] In the future, rising temperatures and increases in the duration and intensity of drought are expected to increase wildfire occurrence and also reduce the effectiveness of prescribed fire.[3,4,5,6]

Hurricanes and rising sea levels are aspects of climate change that will have a tremendous effect on coastal ecosystems in the Southeast. Historically, coastal ecosystems in the region have adjusted to sea level rise via vertical and/or horizontal movement across the landscape.[125,129,200,201] As sea levels rise in the future, some coastal ecosystems will be submerged and converted to open water, and some coastal ecosystems will move inland at the expense of upslope and upriver ecosystems.[203,204] Since coastal terrestrial and freshwater ecosystems are highly sensitive to increases in inundation and/or salinity, sea level rise will result in the comparatively rapid conversion of these systems to tidal saline habitats. In addition to sea level rise, climate change is expected to increase the impacts of hurricanes; the high winds, storm surges, inundation, and salts that accompany hurricanes will have large ecological impacts to terrestrial and freshwater ecosystems.[209,210]

Climate change is expected to intensify the hydrologic cycle and increase the frequency and severity of extreme events. Extreme drought events are expected to become more frequent and severe. Drought and extreme heat can result in tree mortality and transform southeastern forested ecosystems.[217,218,219,220,221,222,223] Drought can also affect aquatic and wetland ecosystems.[224,225,226,227,228,229,232] Extreme rainfall events are also expected to become more frequent and severe in the future. The prolonged inundation and lack of oxygen that result from extreme rainfall events can also result in mortality and large impacts to natural systems.[233] In combination, future increases in both extreme drought and extreme rainfall are expected to transform many southeastern ecosystems.

Warming ocean temperatures due to climate change are expected to have a large effect on marine and coastal ecosystems.[234,235,236] Many species are sensitive to small changes in ocean temperature; hence, the distribution and abundance of marine organisms are expected to be greatly altered by increasing ocean temperatures. For example, the distribution of tropical herbivorous fish has been expanding in response to warmer waters, which has resulted in the tropicalization of some temperate marine ecosystems and decreases in the cover of valuable macroalgal plant communities.[179] A decrease in the growth of sea turtles in the West Atlantic has been linked to higher ocean temperatures.[237] The impacts to coral reef ecosystems have been and are expected to be particularly dire. Coral reef mortality in the Florida Keys and across the globe has been very high in recent decades, due in part to warming ocean temperatures, nutrient enrichment, overfishing, and coastal development.[240,241,242,243,244] Coral elevation and volume in the Florida Keys have been

declining in recent decades,[245] and present-day temperatures in the region are already close to bleaching thresholds; hence, it is likely that many of the remaining coral reefs in the Southeast will be lost in the coming decades.[246,247] In addition to warming temperatures, accelerated ocean acidification is also expected to contribute to coral reef mortality and decline.[248,249]

Major uncertainties

In the Southeast, winter temperature extremes, fire regimes, sea level fluctuations, hurricanes, extreme rainfall, and extreme drought all play critical roles and greatly influence the distribution, structure, and function of species and ecosystems. Changing climatic conditions (particularly, changes in the frequency and severity of climate extremes) are, however, difficult to replicate via experimental manipulations; hence, ecological responses to future climate regimes have not been fully quantified for all species and ecosystems. Natural ecosystems are complex and governed by many interacting biotic and abiotic processes. Although it is possible to make general predictions of climate change effects, specific future ecological transformations can be difficult to predict, especially given the number of interacting and changing biotic and abiotic factors in any specific location. Uncertainties in the range of potential future changes in multiple and concurrent facets of climate and land-use change also affect our ability to predict changes to natural systems.

Description of confidence and likelihood

There is *high confidence* that climate change (e.g., changing winter temperatures extremes, changing fire regimes, rising sea levels and hurricanes, warming ocean temperatures, and more extreme rainfall and drought) will *very likely* affect natural systems in the Southeast region. These climatic drivers play critical roles and greatly influence the distribution, structure, and functioning of ecosystems; hence, changes in these climatic drivers will transform ecosystems in the region and greatly alter the distribution and abundance of species.

Key Message 4

Economic and Health Risks for Rural Communities

Rural communities are integral to the Southeast's cultural heritage and to the strong agricultural and forest products industries across the region. More frequent extreme heat episodes and changing seasonal climates are projected to increase exposure-linked health impacts and economic vulnerabilities in the agricultural, timber, and manufacturing sectors (*very likely, high confidence*). By the end of the century, over one-half billion labor hours could be lost from extreme heat-related impacts (*likely, medium confidence*). Such changes would negatively impact the region's labor-intensive agricultural industry and compound existing social stresses in rural areas related to limited local community capabilities and associated with rural demography, occupations, earnings, literacy, and poverty incidence (*very likely, high confidence*). Reduction of existing stresses can increase resilience (*very likely, high confidence*).

Description of evidence base

Analysis of the sensitivity of some manufacturing sectors to climate changes anticipates secondary risks associated with crop and livestock productivity.[64,255]

Multiple analyses anticipate that energy- or water-intensive industries could face water stress and increased energy costs.[8,64,255,256]

A large body of evidence addresses the sensitivity of many crops grown in the Southeast to changing climate conditions including increased temperatures, decreased summer rainfall, drought, and change in the timing and duration of chill periods.[7,35] Extensive research documents livestock sensitivity to heat stress.[7]

Multiple lines of evidence indicate that forests are likely to be impacted by changing climate, particularly moisture regimes and potential changes in wildfire activity.[191,195,272,274] There is extensive research on heat-related illness and mortality among those living and working in the Southeast. While there is more evidence focused on urban areas, limited research has identified higher levels of heat-related illness in rural areas.[280,281] Research on occupational heat-related mortality identifies some of the Nation's highest levels in southeastern states.[282] Computer model simulations of heat-related reductions in labor productivity anticipate the greatest losses will occur in the Southeast. However, these models do not account for adaptations that may reduce estimated losses.[35,64] By the end of the century, mean annual electricity costs are estimated at $3.3 billion each year under RCP8.5 (model range: $2.4 to $4.2 billion; in 2015 dollars, undiscounted) and mean $1.2 billion each year under RCP4.5 (model range $0.9 to $1.9 billion; in 2015 dollars, undiscounted).[35]

Rural communities tend to be vulnerable due to factors such as demography, occupations, earnings, literacy, and poverty incidence.[8,9,10,250,283,284,305] Reducing the stress created by such factors can improve resilience.[9,284] The availability and accessibility of planning and health services to support coping with climate-related stresses are limited in the rural Southeast.[288,289]

Major uncertainties

There are limited studies documenting direct connections between climate changes and economic impacts. Models are limited in their ability to incorporate adaptation that may reduce losses. These factors restrict the potential to strongly associate declines in agricultural and forest productivity with the level of potential economic impact.

Projections of potential change in the frequency and extent of wildfires depend in part on models of future population growth and human behavior, which are limited, adding to the uncertainty associated with climate and forest modeling.

Many indicators of vulnerability are dynamic, so that adaptation and other changes can affect the patterns of vulnerability to heat and other climate stressors over time. Limited studies indicate concerns over the planning and preparedness of capacity at local levels; however, information is limited.

Projected labor hours lost vary by global climate model, time frame, and scenario, with a mean of 0.57 and a model range of 0.34–0.82 billion labor hours lost each year for RCP8.5 by 2090. The annual mean projected losses are roughly halved (0.28 billion labor hours) and with a model range from 0.19 to 0.43 billion labor hours lost under RCP4.5 by 2090.[35]

Description of confidence and likelihood

There is *high confidence* that climate change (e.g., rising temperatures, changing fire regimes, rising sea levels, and more extreme rainfall and drought) will *very likely* affect agricultural and forest products industries, potentially resulting in economic impacts. There is *high confidence* that increases in temperature are *very likely* to increase heat-related illness, deaths, and loss of labor productivity without greater adaptation efforts.

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On the Web: https://nca2018.globalchange.gov/chapter/caribbean

20 U.S. Caribbean

San Juan, Puerto Rico

Key Message 1

Freshwater

Freshwater is critical to life throughout the Caribbean. Increasing global carbon emissions are projected to reduce average rainfall in this region by the end of the century, constraining freshwater availability, while extreme rainfall events, which can increase freshwater flooding impacts, are expected to increase in intensity. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers. Increasing variability in rainfall events and increasing temperatures will likely alter the distribution of ecological life zones and exacerbate existing problems in water management, planning, and infrastructure capacity.

Key Message 2

Marine Resources

Marine ecological systems provide key ecosystem services such as commercial and recreational fisheries and coastal protection. These systems are threatened by changes in ocean surface temperature, ocean acidification, sea level rise, and changes in the frequency and intensity of storm events. Degradation of coral and other marine habitats can result in changes in the distribution of species that use these habitats and the loss of live coral cover, sponges, and other key species. These changes will likely disrupt valuable ecosystem services, producing subsequent effects on Caribbean island economies.

Key Message 3

Coastal Systems

Coasts are a central feature of Caribbean island communities. Coastal zones dominate island economies and are home to critical infrastructure, public and private property, cultural heritage, and natural ecological systems. Sea level rise, combined with stronger wave action and higher storm surges, will worsen coastal flooding and increase coastal erosion, likely leading to diminished beach area, loss of storm surge barriers, decreased tourism, and negative effects on livelihoods and well-being. Adaptive planning and nature-based strategies, combined with active community participation and traditional knowledge, are beginning to be deployed to reduce the risks of a changing climate.

Key Message 4

Rising Temperatures

Natural and social systems adapt to the temperatures under which they evolve and operate. Changes to average and extreme temperatures have direct and indirect effects on organisms and strong interactions with hydrological cycles, resulting in a variety of impacts. Continued increases in average temperatures will likely lead to decreases in agricultural productivity, changes in habitats and wildlife distributions, and risks to human health, especially in vulnerable populations. As maximum and minimum temperatures increase, there are likely to be fewer cool nights and more frequent hot days, which will likely affect the quality of life in the U.S. Caribbean.

Key Message 5

Disaster Risk Response to Extreme Events

Extreme events pose significant risks to life, property, and economy in the Caribbean, and some extreme events, such as flooding and droughts, are projected to increase in frequency and intensity. Increasing hurricane intensity and associated rainfall rates will likely affect human health and well-being, economic development, conservation, and agricultural productivity. Increased resilience will depend on collaboration and integrated planning, preparation, and responses across the region.

Key Message 6

Increasing Adaptive Capacity Through Regional Collaboration

Shared knowledge, collaborative research and monitoring, and sustainable institutional adaptive capacity can help support and speed up disaster recovery, reduce loss of life, enhance food security, and improve economic opportunity in the U.S. Caribbean. Increased regional cooperation and stronger partnerships in the Caribbean can expand the region's collective ability to achieve effective actions that build climate change resilience, reduce vulnerability to extreme events, and assist in recovery efforts.

Executive Summary

Historically, the U.S. Caribbean region has experienced relatively stable seasonal rainfall patterns, moderate annual temperature fluctuations, and a variety of extreme weather events, such as tropical storms, hurricanes, and drought. However, the Caribbean climate is changing and is projected to be increasingly variable as levels of greenhouse gases in the atmosphere increase.

The high percentage of coastal area relative to the total island land area in the U.S. Caribbean means that a large proportion of the region's people, infrastructure, and economic activity are vulnerable to sea level rise, more frequent intense rainfall events and associated coastal flooding, and saltwater intrusion. High levels of exposure and sensitivity to risk in the U.S. Caribbean region are compounded by a low level of adaptive capacity, due in part to the high costs of mitigation and adaptation measures relative to the region's gross domestic product, particularly when compared to continental U.S. coastal areas.[1] The limited geographic and economic scale of Caribbean islands means that disruptions from extreme climate-related events, such as droughts and hurricanes, can devastate large portions of local economies and cause widespread damage to crops, water supplies, infrastructure, and other critical resources and services.[1]

The U.S. Caribbean territories of Puerto Rico and the U.S. Virgin Islands (USVI) have distinct differences in topography, language, population size, governance, natural and human resources, and economic capacity. However, both are highly dependent on natural and built coastal assets; service-related industries account for more than 60% of the USVI economy. Beaches, affected by sea level rise and erosion, are among the main tourist attractions. In Puerto Rico, critical infrastructure (for example, drinking water pipelines and pump stations, sanitary pipelines and pump stations, wastewater treatment plants, and power plants) is vulnerable to the effects of sea level rise, storm surge, and flooding. In the USVI, infrastructure and historical buildings in the inundation zone for sea level rise include the power plants on both St. Thomas and St. Croix; schools; housing communities; the towns of Charlotte Amalie, Christiansted, and Frederiksted; and pipelines for water and sewage.

Climate change will likely result in water shortages due to an overall decrease in annual rainfall, a reduction in ecosystem services, and increased risks for agriculture, human health, wildlife, and socioeconomic development in the U.S. Caribbean. These shortages would result from some locations within the Caribbean experiencing longer dry seasons and shorter, but wetter, wet seasons in the future. [2,3,4,5,6,7,8] Extended dry seasons are projected to increase fire likelihood.[9,10] Excessive rainfall, coupled with poor construction practices, unpaved roads, and steep slopes, can exacerbate erosion rates and have adverse effects on reservoir capacity, water quality, and nearshore marine habitats.

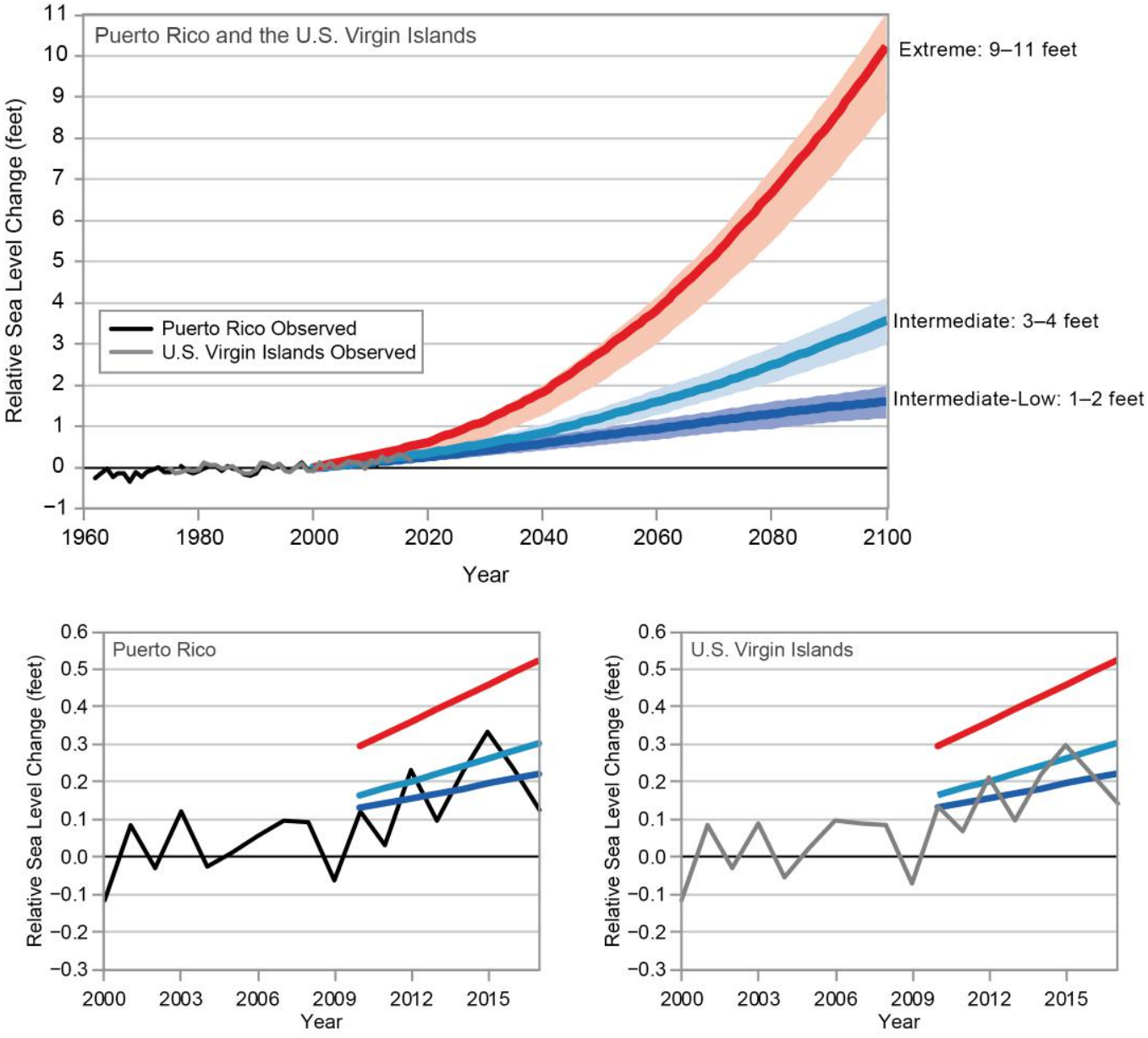
Ocean warming poses a significant threat to the survival of corals and will likely also cause shifts in associated habitats that compose the coral reef ecosystem. Severe, repeated, or prolonged periods of high temperatures leading to extended coral bleaching can result in colony death. Ocean acidification also is likely to diminish the structural integrity of coral habitats. Studies show that major shifts in fisheries distribution and changes to the structure and composition of marine habitats adversely affect food security, shoreline protection, and economies throughout the Caribbean.

In Puerto Rico, the annual number of days with temperatures above 90°F has increased over the last four and a half decades. During that period, stroke and cardiovascular disease, which are influenced by such elevated temperatures,

became the primary causes of death.[11,12] Increases in average temperature and in extreme heat events will likely have detrimental effects on agricultural operations throughout the U.S. Caribbean region.[13,14] Many farmers in the tropics, including the U.S. Caribbean, are considered small-holding, limited resource farmers and often lack the resources and/or capital to adapt to changing conditions. [15]

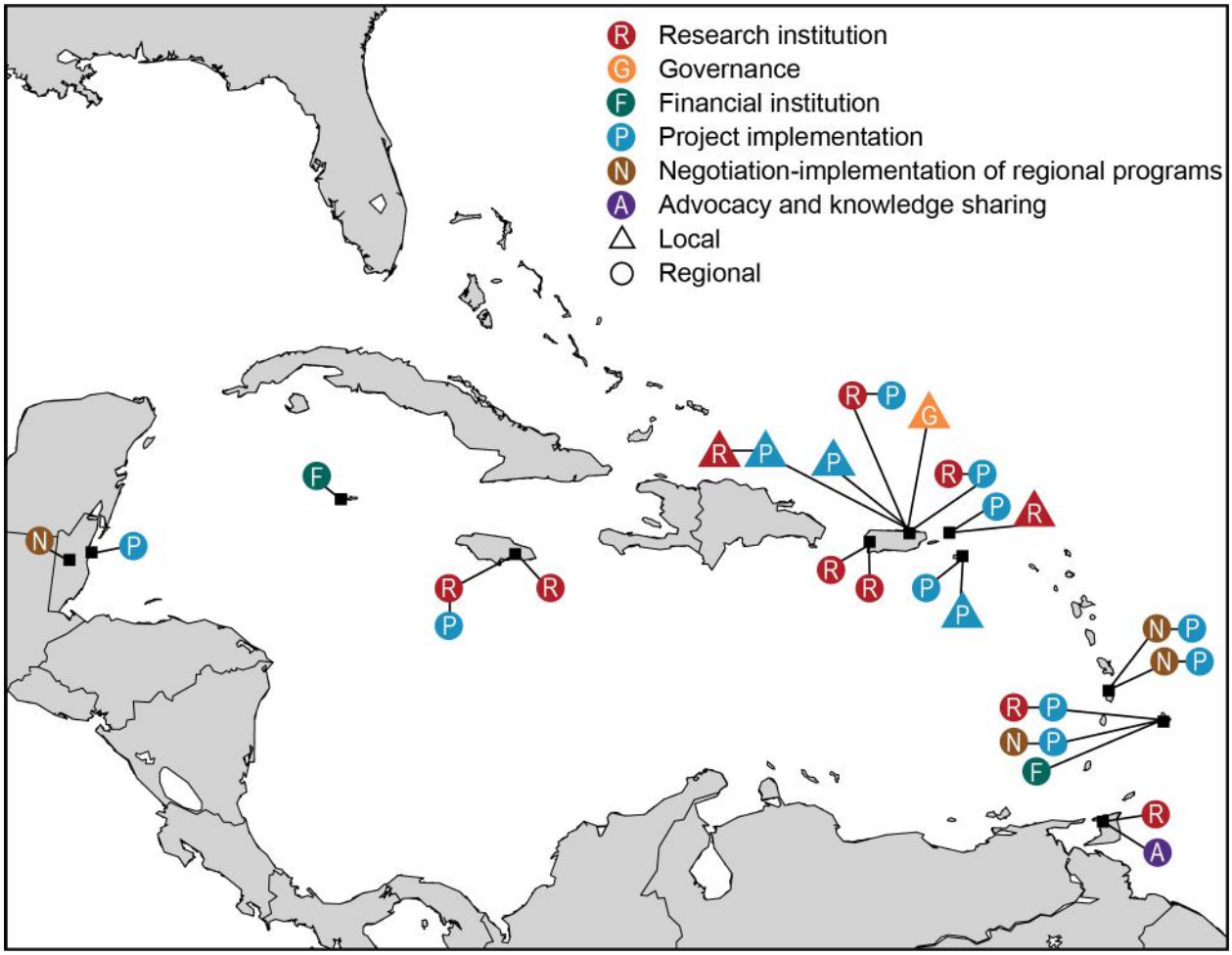
Most Caribbean countries and territories share the need to assess risks, enable actions across scales, and assess changes in ecosystems to inform decision-making on habitat protection under a changing climate.[16,17] U.S. Caribbean islands have the potential to improve adaptation and mitigation actions by fostering stronger collaborations with Caribbean initiatives on climate change and disaster risk reduction.

Observed and Projected Sea Level Rise



(top) Observed sea level rise trends in Puerto Rico and the U.S. Virgin Islands reflect an increase in sea level of about 0.08 inches (2.0 mm) per year for the period 1962–2017 for Puerto Rico and for 1975–2017 for the U.S. Virgin Islands. The bottom panels show a closer look at more recent trends from 2000 to 2017 that measure a rise in sea level of about 0.24 inches (6.0 mm) per year. Projections of sea level rise are shown under three different scenarios of Intermediate-Low (1–2 feet), Intermediate (3–4 feet), and Extreme (9–11 feet) sea level rise. The scenarios depict the range of future sea level rise based on factors such as global greenhouse gas emissions and the loss of glaciers and ice sheets. *From Figure 20.6. (Sources: NOAA NCEI and CICS-NC).*

Climate Risk Management Organizations



Some of the organizations working on climate risk assessment and management in the Caribbean are shown. Joint regional efforts to address climate challenges include the implementation of adaptation measures to reduce natural, social, and economic vulnerabilities, as well as actions to reduce greenhouse gas emissions. See the online version of this figure at http://nca2018.globalchange.gov/chapter/20#fig-20-18 for more details. *From Figure 20.18 (Sources: NOAA and the USDA Caribbean Climate Hub)*.

Background

Puerto Rico and the U.S. Virgin Islands (USVI) are rich in biodiversity, cultural heritage, and natural resources. More than 3.5 million inhabitants depend on the region's natural resources and environmental services for their well-being, livelihoods, local economies, and cultural identities. Changing climate and weather patterns interacting with human activities, are affecting land use, air quality, and resource management and are posing growing risks to food security, the economy, culture, and ecosystems services.

The U.S. Caribbean (Figure 20.1) includes the inhabited commonwealth islands of Puerto Rico, Vieques, and Culebra (with a combined population of 3.4 million), along with the inhabited territorial islands of St. Croix, St. Thomas, St. John, and Water Island (with a combined population of 104,000). In addition to the principal islands, the U.S. Caribbean includes over 800 smaller islands and cays, diverse cultural and historical resources, and a rich matrix of marine and terrestrial ecosystems. The region's physical geography includes nearshore and open ocean marine areas; coastal wetlands, hills, and plains; limestone (or karst) hills; and interior mountains. Average rainfall amounts vary widely across the region, and social and ecological systems are diverse. Puerto Rico and the USVI share many vulnerabilities with coastal states and the Pacific Islands but lack much of the capacity available to the continental United States.

Shared Vulnerabilities of U.S. Caribbean and Pacific Islands

The U.S. Caribbean islands face many of the same climate change related challenges as Hawai'i and the U.S.-Affiliated Pacific Islands (Ch. 27: Hawai'i & Pacific Islands), including

- isolation and dependence on imports, making islands more vulnerable to climate-related impacts;
- critical dependence on local sources of freshwater (Ch. 27, KM 1);
- temperature increases that will further reduce supply and increase demand on freshwater (Ch. 27, KM 1);
- vulnerability to drought in ways that differ from mainland regions (Ch. 27, KM 1);
- a projected significant decrease in rainfall in all (Caribbean) or parts (Hawai'i and Pacific Islands) of these regions (Ch. 27, KM 1);
- sea level rise, coastal erosion, and increasing storm impacts that threaten lives, critical infrastructure, and livelihoods on islands (Ch. 27, KM 2–4);
- prominent concerns about the economic consequences of coastal threats (Ch. 27, KM 3);
- coral bleaching and mortality due to warming ocean surface waters and ocean acidification (Ch. 27, KM 4); and
- threats to critical economic marine resources, including fisheries (Ch. 27, KM 4).

U.S. Caribbean Region

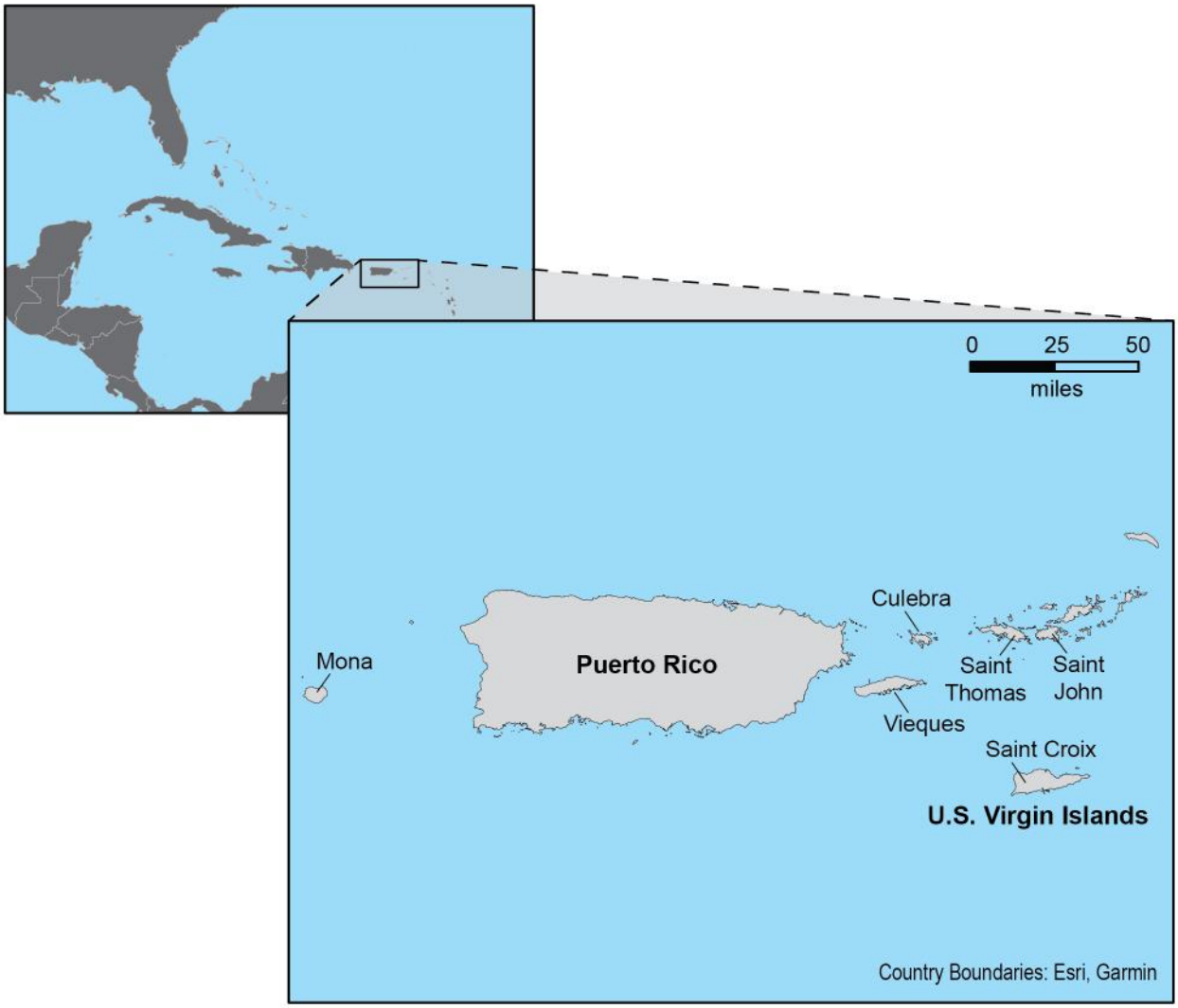


Figure 20.1: The U.S. Caribbean includes the Commonwealth of Puerto Rico and the territory of the U.S. Virgin Islands. The region includes seven inhabited islands and nearly 800 smaller islands and cays.

The islands also have unique issues related to data availability and the capacity to develop datasets comparable to those available for the continental United States. For example, the small size of the islands, particularly the USVI, affects the availability and accuracy of downscaled climate data and projections, similar to the Pacific Islands (Ch. 27: Hawai'i & Pacific Islands). Additionally, differences in the natural and social systems, and in information availability for Puerto Rico and the USVI, affect the degree of vulnerability to climate change and extreme climate events. This is reflected in different needs, priorities, and approaches to reducing vulnerability between Puerto Rico and the USVI. Historically, the U.S. Caribbean region has experienced relatively stable seasonal rainfall patterns, moderate annual temperature fluctuations, and a variety of extreme weather events, such as tropical storms, hurricanes, and drought. However, these patterns are changing and are projected to be increasingly variable as atmospheric greenhouse gas concentrations increase. Having evolved with these historic climate conditions, and given the small size and relatively isolated nature of these islands, Caribbean social, economic, and ecological systems are likely to be more sensitive to changes in temperature and precipitation than similar systems in the mainland United States (Figure 20.2).[18,19]

Climate Indicators and Impacts

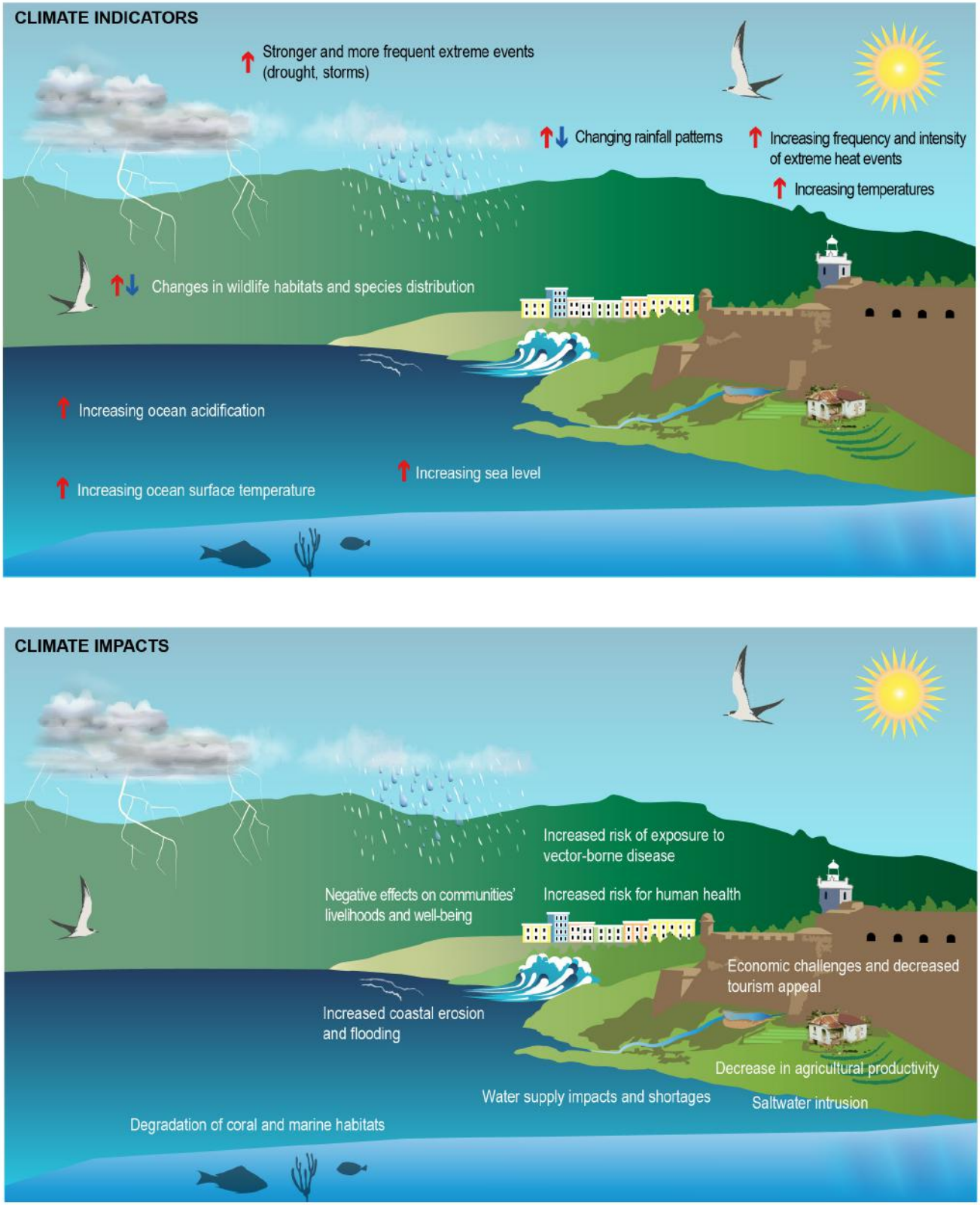


Figure 20.2: (top) Key indicators for monitoring climate variability and change in the U.S. Caribbean include sea level rise, ocean temperature and acidity, air temperature, rainfall patterns, frequency of extreme events, and changes in wildlife habitats. (bottom) Changes in these climate indicators result in environmental and social impacts to natural ecosystems, infrastructure, and society, including degradation of coral and marine habitats, increased coastal flooding and erosion, decrease in agricultural productivity, water supply shortages, negative effects on communities' livelihoods and on human health, as well as economic challenges and decreased tourism appeal. Source: Puerto Rico Department of Natural and Environmental Resources.

The vulnerability of the U.S. Caribbean region is influenced by global, regional, and local factors. The region is sensitive to large-scale patterns of natural variability in both the Atlantic and Pacific tropical basins, such as the El Niño–Southern Oscillation and the Atlantic Multidecadal Oscillation.[20] Climate variations due to these large-scale patterns directly impact the U.S. Caribbean because the islands largely rely on surface waters and consistent annual rainfall to meet freshwater demands. The high percentage of coastal areas relative to the total island land area means that a large proportion of the region's people, infrastructure, and economic activity are vulnerable to sea level rise, more frequent intense rainfall events and associated coastal flooding, and saltwater intrusion. As on islands worldwide, there are strong socioeconomic and cultural ties to diminishing marine resources and services, as well as economic dependence on tourism and imported goods.[1,13,14,21] High levels of exposure and sensitivity to risk in the region are compounded by a low level of adaptive capacity, due in part to the high costs of mitigation and adaptation measures relative to the region's gross domestic product, particularly when compared to continental U.S. coastal areas.[1]

The people of the U.S. Caribbean rely heavily on imported food and other goods and services, leaving them critically exposed to climate-related disruptions in transportation systems as well as vulnerabilities associated with source geographies.[22] Crop species key to regional economies and food security—such as coffee, plantains, and mangoes—have evolved in narrower climatic niches relative to temperate crops and are often detrimentally affected by relatively small shifts in temperature, humidity, and rainfall.[13,23,24] The limited geographic and economic scale of Caribbean islands means that disruptions from extreme climate-related events, such as droughts and hurricanes, can devastate large portions of local economies and cause widespread damage to crops, water supplies, infrastructure, and other critical resources and services.[1,25]

Observed and Projected Climate Change

The *Climate Science Special Report* (CSSR)[26] provides an in-depth assessment of observed and projected climate change in the continental United States. Because this level of assessment was not available for the U.S. Caribbean region, this section provides a brief overview of observed trends and future projections of five climate variables that are relevant to assessing climate change risk in the region: temperature, precipitation, sea surface temperature, ocean acidification, and sea level rise.

Temperature. Annual average temperatures in the U.S. Caribbean have fluctuated over the last century. However, since 1950, temperatures have increased by about 1.5°F in Puerto Rico.[27] Projected increases under both a lower and higher scenario (RCP4.5 and RCP8.5) are expected in both average and extreme temperatures, which will lead to more days per year over 95°F and more nights per year over 85°F.[28] Global climate models project about a 1.5°F to 4°F increase in average temperatures for the U.S. Caribbean by 2050. End-of-century estimates show temperature increases as high as about 9°F under a higher scenario (RCP8.5; Figure 20.3).[7]

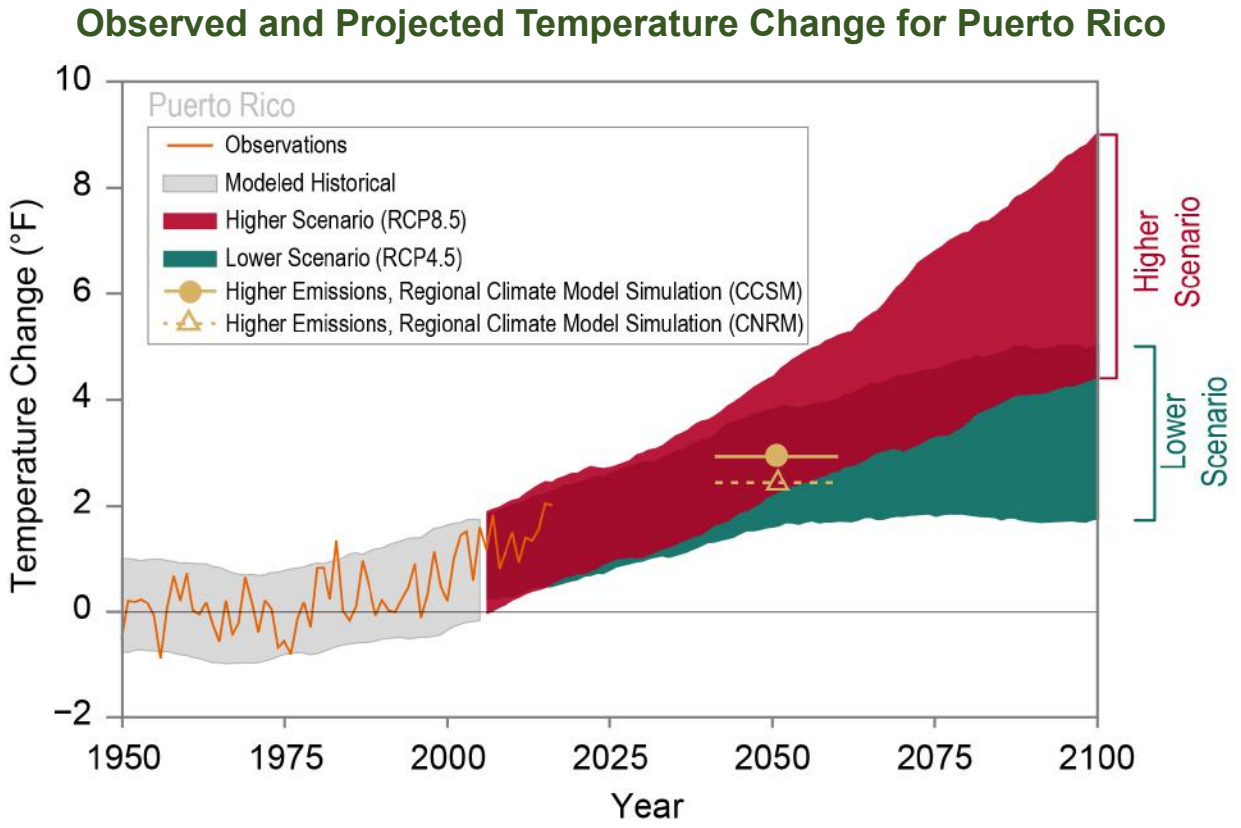


Figure 20.3: Observed and projected temperature changes are shown as compared to the 1951–1980 average. Observed data are for 1950–2017, and the range of model simulations for the historical period is for 1950–2005. The range of projected temperature changes from global climate models is shown for 2006–2100 under a lower (RCP4.5) and a higher (RCP8.5) scenario (see the Scenario Products section of App. 3). Projections from two regional climate models are shown for 2036–2065, and they align with those from global models for the same period.[29,30] Sources: NOAA NCEI, CICS-NC, and USGS.

Precipitation. Globally, subtropical regions are expected to become drier in the future, especially in regions such as the U.S. Caribbean where oceans have the largest influence on local precipitation patterns.[31] Climate model results consistently project significant drying in the U.S. Caribbean region by the middle of this century, specifically, a decline of more than 10% in annual precipitation under the higher scenario (RCP8.5; Figure 20.4).[7,28,30,32] The magnitude of this projected drying, particularly for climate scenarios with the highest amounts of warming, is in general lower in the most recently developed climate models.[28] The region is likely to experience more intense rainfall events associated with tropical cyclones;[33] however, uncertainty remains regarding various aspects of extreme rainfall within the region, such as the frequency and duration of extreme rainfall events associated with tropical cyclones.[28,34] For instance, one study[34] finds less frequent extreme rainfall events on average in the future at sub-daily and daily timescales, while another[28] finds more frequent extreme rainfall events that exceed 3 inches of rain in a day, as well as more intense rainfall associated with tropical cyclones.[28,33]

Sea surface temperature and ocean acidification. Globally, surface ocean waters have warmed by about 1.3°F per century between 1900 and 2016.[35] Over the period 1955–2016, the waters of the northeast Caribbean increased in temperature at a rate of 0.23°F per decade,[36] and over the last two decades, the sea surface warming rate has reached 0.43°F per decade (Figure 20.5).

Projected Precipitation Change for Puerto Rico

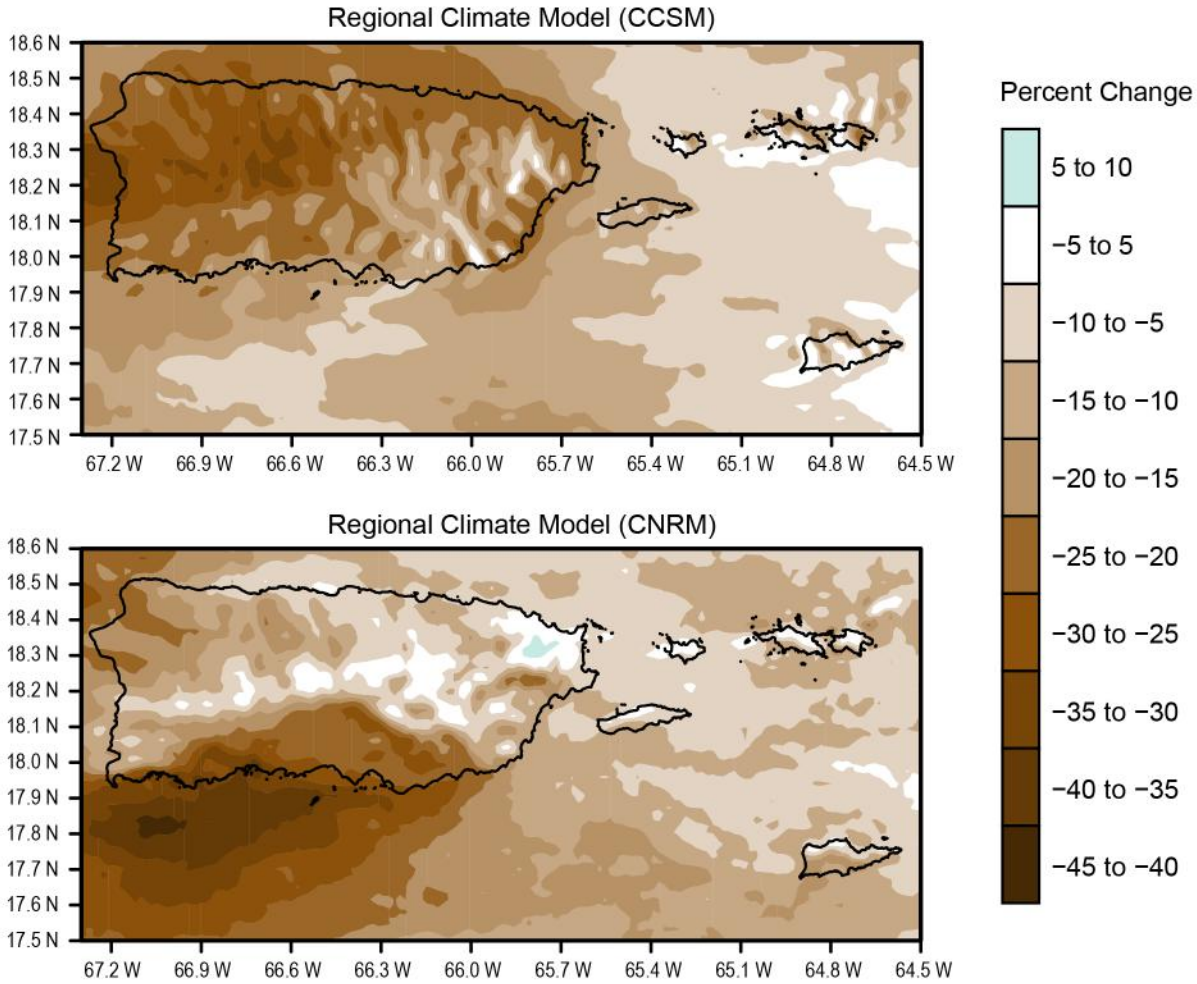


Figure 20.4: This figure shows the projected percent change in annual precipitation over the U.S. Caribbean region for the period 2040–2060 compared to 1985–2005 based on the results of two regional climate model simulations.[29,30] These simulations downscale two global models for the higher scenario (RCP8.5)[26] and show that within-island changes are projected to exceed a 10% reduction in annual rainfall. Uncertainty remains as to the location of the largest reductions within the islands. Projections of precipitation change for the U.S. Virgin Islands are particularly uncertain because of model limitations related to resolving these smaller islands. Source: Bowden et al. 2018.[30]

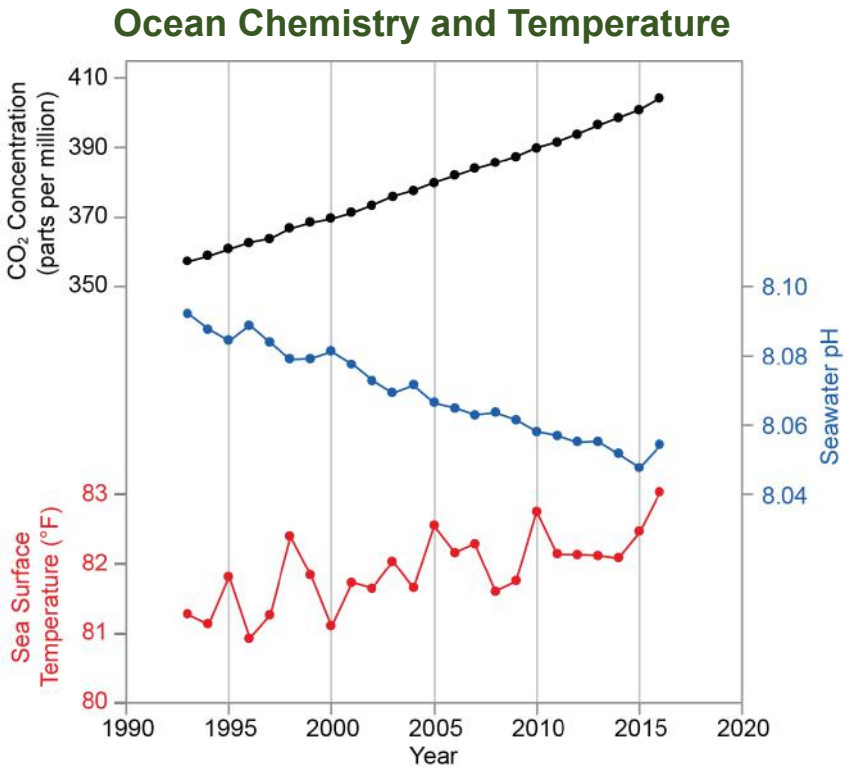


Figure 20.5: This figure represents an annual time series from 1993 to 2016 of atmospheric carbon dioxide (CO_2; black line), sea surface temperature (red line), and seawater pH (blue line) for the Caribbean region. The Caribbean ocean is subject to changes in surface pH and temperature due to the increase in atmospheric CO_2 concentrations. The oceans have the capacity to not only absorb heat from the air (leading to ocean warming) but also to absorb some of the CO_2 in the atmosphere, causing more acidic (lower pH) oceans. Continued ocean acidification and warming have potentially detrimental consequences for marine life and dependent coastal communities in the Caribbean islands. Source: University of Puerto Rico.

Sea level rise. Since the middle of 20th century, relative sea levels have risen by about 0.08 inches (2 mm) per year on average along the coasts of Puerto Rico and the USVI.[37,38] However, rates have been slowly accelerating since the early 2000s and show noticeable acceleration (by a factor of about 3) starting in about 2010–2011. This recent accelerating trend is in agreement with what has been observed along the southeastern U.S. seaboard, and rates of global and regional relative sea level rise are projected to continue to increase substantially this century, largely dependent on the amount of future greenhouse gas emissions. Under the Intermediate-Low, Intermediate, and Extreme scenarios, relative sea levels are projected to rise by about 0.8 feet, 1.2 feet, or 2.8 feet (24 cm, 37 cm, or 84 cm), respectively, by 2050 across the region compared to levels in 2000 and by about 1.6 feet, 3.6 feet, or 10.2 feet (0.5 m, 1.1 m, or 3.1 m), respectively, by 2100 (Figure 20.6).[38] Additionally, the region may experience more than the global average increase under the higher scenarios in response to changes in the Earth's gravitational field and rotation due to melting of land ice, ocean circulation, and vertical land motion.

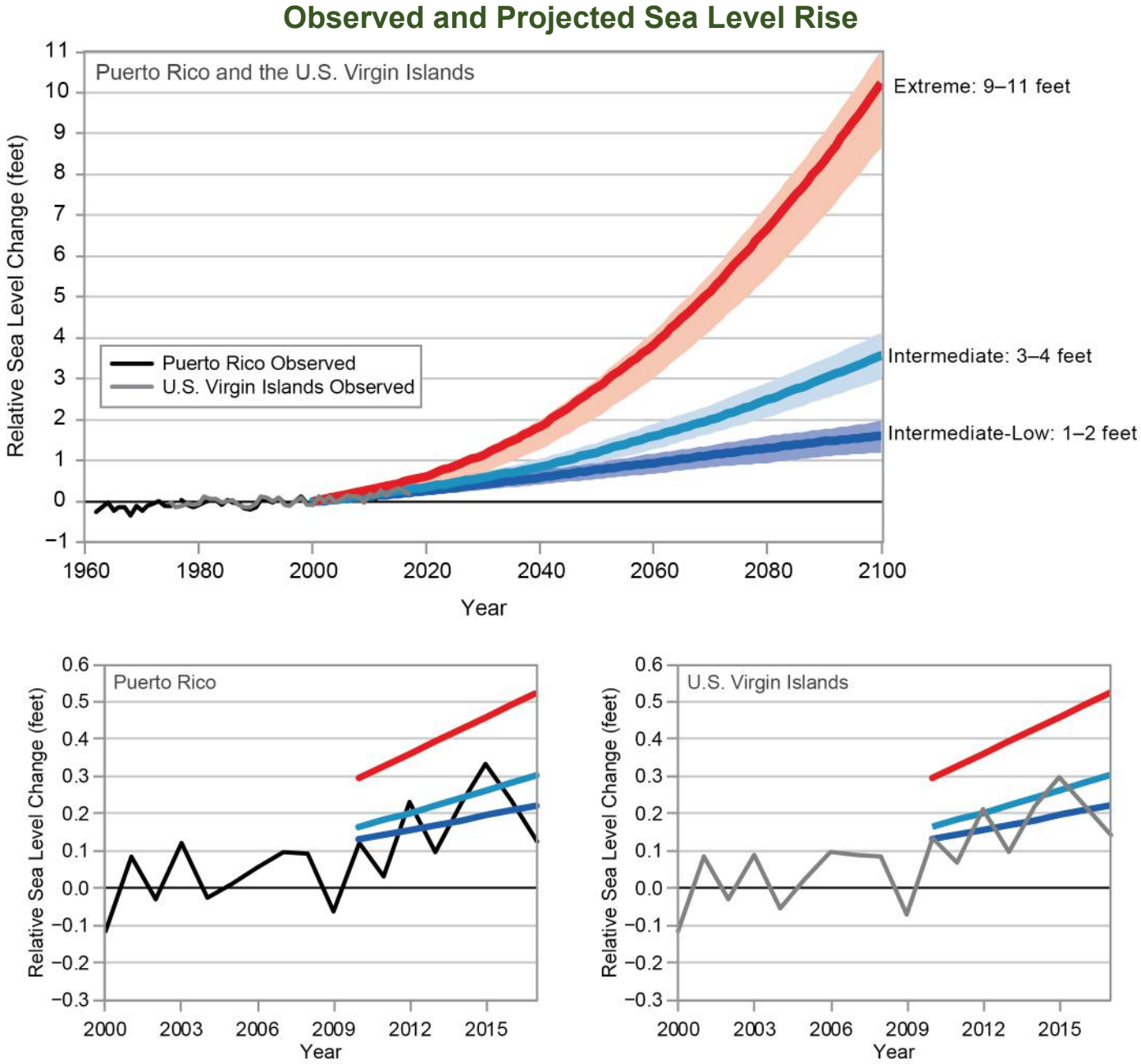


Figure 20.6: (top) Observed sea level rise trends in Puerto Rico and the U.S. Virgin Islands reflect an increase in sea level of about 0.08 inches (2.0 mm) per year for the period 1962–2017 for Puerto Rico and for 1975–2017 for the U.S. Virgin Islands. The bottom panels show a closer look at more recent trends from 2000 to 2017 that measure a rise in sea level of about 0.24 inches (6.0 mm) per year. Projections of sea level rise are shown under three different scenarios of Intermediate-Low (1–2 feet), Intermediate (3–4 feet), and Extreme (9–11 feet) sea level rise. The scenarios depict the range of future sea level rise based on factors such as global greenhouse gas emissions and the loss of glaciers and ice sheets. Sources: NOAA NCEI and CICS-NC.

Key Message 1

Freshwater

Freshwater is critical to life throughout the Caribbean. Increasing global carbon emissions are projected to reduce average rainfall in this region by the end of the century, constraining freshwater availability, while extreme rainfall events, which can increase freshwater flooding impacts, are expected to increase in intensity. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers. Increasing variability in rainfall events and increasing temperatures will likely alter the distribution of ecological life zones and exacerbate existing problems in water management, planning, and infrastructure capacity.

Linkage Between Climate Change and Regional Risks

Freshwater availability is a function of rainfall, temperature, evapotranspiration (evaporation and transpiration from plants), land cover, watershed characteristics, water use and management, and water quality, and is dependent on the intensity, duration, frequency, and distribution of rainfall within the island. Availability is also affected by seasonal and annual variability in rainfall as well as long-term climate trends. Climate change will likely result in water shortages (due to an overall decrease in annual rainfall), a reduction in ecosystem services, and increased risks for agriculture, human health, wildlife, and socioeconomic development in the U.S. Caribbean.

Rainfall in the U.S. Caribbean is highly variable across space and time, complicating analyses of trends.[39] However, past occurrences of drought or excessive rainfall provide insights into vulnerabilities that may be indicative of the future. Droughts and extreme rainfall events in recent years have resulted in economic loss and social disruption. The most recent drought of 2014–2016 in Puerto Rico and the USVI resulted in severe losses to the agriculture sector, implementation of water rationing by the Puerto Rico Aqueduct and Sewer Authority, drying of wetlands, and reduced habitat quality for freshwater biota, including threatened and endangered species such as the Antillean manatee.[40]

Freshwater resources are primarily surface waters. In the USVI, desalination plants provide some of the public water supply. In Puerto Rico, management and sustainable use of water resources and infrastructure have been problematic for decades, particularly in terms of storage, distribution, and quality of the public water supply.[41,42] In 2013, 57.4% of all water produced was lost in distribution.[42] Recurring droughts and sedimentation-induced reductions in reservoir storage present a challenge to freshwater availability.[43] One of the principal sources of potable water for Puerto Rico, Loíza reservoir, has lost nearly 40% of its original storage capacity due to sedimentation.[44,45]

Future Climate Change Relevant to Regional Risks

The greatest risk to freshwater resources may be reduced availability due to drying trends.[46] Large uncertainty remains in terms of projected rainfall intensity, duration, and frequency. However, hydrologic model simulations indicate that major reservoirs in Puerto Rico could enter permanent supply deficit as early as 2025 under a higher emissions scenario (SRES A2) (see the Scenario Products section of App. 3) and by 2040 under a lower emissions scenario (SRES B1; Figure 20.7).[46]

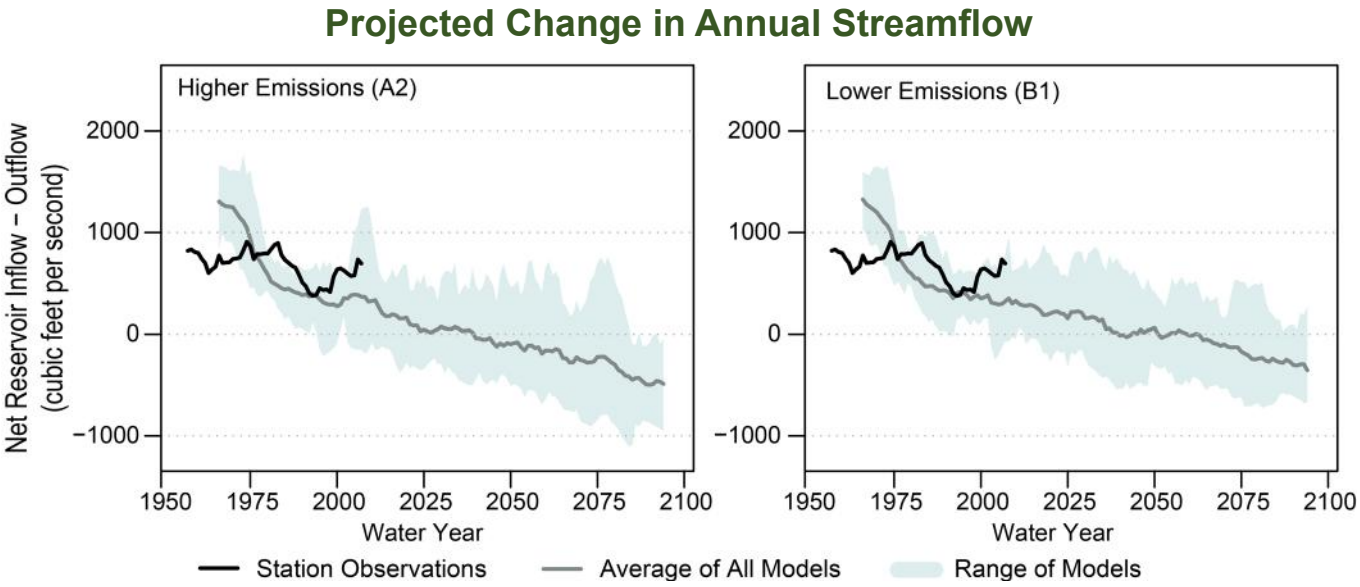


Figure 20.7: This figure shows ten-year moving averages of projected annual streamflow leaving Lago La Plata and Lago Loíza. Projections were developed using an estimation of water supply entering the reservoirs and an estimation of withdrawals. The former was developed using a range of global climate models (GCMs; shading indicates averages from all GCMs used in the study) and the mean of that range (gray line). The latter was developed using a conservative population growth rate. Annual streamflow is modeled under a higher emissions scenario (SRES A2; left panel) and a lower emissions scenario (SRES B1; right panel). The solid black line is the historical streamflow through 2012.[46] It is important to note these are the best estimates available for projected streamflow and use the older generation of GCMs, which project more drying for the region.[28] Source: adapted from Van Beusekom et al. 2016.[46]

Studies indicate that some locations within the Caribbean may experience longer dry seasons and shorter, but wetter, wet seasons in the future.[2,3,4,5,6,8] Extended dry seasons are projected to increase fire likelihood[9,10] and affect plant phenology (the timing of important biological events), as well as wildlife dependent on fruiting and flowering.[47] Excessive rainfall coupled with poor construction practices, unpaved roads, and steep slopes, which are typical of the Caribbean islands, can exacerbate erosion rates and reduce reservoir capacity, water quality, and nearshore habitat quality.

Rainfall also drives the distribution of ecological life zones in the U.S. Caribbean.[48] Projected decreases in rainfall foreshadow relative increases in dry life zones and the shrinkage and disappearance of wetter life zones. Ecological implications of these shifts include changes in biodiversity, carbon cycling, forest composition and structure, and nutrient and water cycling.[7] Vulnerable life zones include the unique rainforest habitats in the Luquillo Mountains of Puerto Rico (Figure 20.8).[8,49,50] Montane species are shifting their ranges upslope and may reach upper elevational limits as temperatures continue to climb.[51] Studies find that cloud levels in the dry season are consistently as low as, or lower than, in the wet season in the Luquillo Mountains, indicating that the cloud forest ecosystem may be more vulnerable to wet-season drought periods than previously assumed.[10]

Cloud Forests Are Vulnerable to Climate Change

Figure 20.8: Tropical montane cloud forests in the Luquillo Mountains of Puerto Rico are characterized by the frequent presence of clouds, reduced tree height, a high number of endemic and endangered species, and high water content of the soil due to reduced sunlight. Cloud forests around the world are vulnerable due to the warming and drying conditions that are expected with climate change.[52] Cloud forests on low mountains are especially vulnerable, as drying and warming conditions can increase the elevation at which clouds form, thereby reducing or possibly eliminating the cloud cover shrouding the mountain peaks.[53,54,55] Photo credit: Grizelle González, USDA Forest Service International Institute of Tropical Forestry.

Challenges, Opportunities, and Success Stories for Reducing Risk

Climate change projections provide new impetus to establish practices that reduce current risks to drought and excessive rain and, by inference, reduce future risks to new conditions. The United Nations Environment Programme has promoted rainwater harvesting in Caribbean Small Island Developing States (SIDS).[56,57] The Puerto Rico Technical Scientific Drought Committee also recommended the use of cisterns and other structural measures to capture rainwater in residential areas of the territory, encouraged their use on existing homes, and recommended making them mandatory for new projects.[40] These systems not only serve as sources for drinking water but also help in storm water management.[58,59,60] Citizens of the USVI are required by law to be directly responsible for their own domestic water supply. The majority of USVI's residents depend on cistern water and use the public source only when they run out of their cistern water.[57]

Application of new technologies is vital if losses from water supply distribution systems are to be reduced. Public freshwater supplies are jeopardized by reservoir sedimentation, which can also be harmful to downstream ecosystems as sedimentation rates are reduced downstream. Improving sediment management practices, such as those identified from prior experiences,[61] can help sustain reservoir capacities and minimize environmental impacts.

Emerging Issues

Managing freshwater and balancing water use among sectors are emerging as two of the most important issues to the U.S. Caribbean islands. Increasing agricultural production will improve food security and the economy but will be challenging, as water availability is likely to decrease over much of the Caribbean.[62] Options for improving water-use efficiency in the agricultural sector include optimizing the management of water infrastructure, applying scientific methods for scheduling irrigation, determining crop water requirements for local crops, using crop suitability modeling to evaluate potential responses to climate change and extreme weather scenarios, plant-breeding for extreme conditions, and implementing methods to improve soil fertility, reduce erosion, and increase carbon storage (Ch. 27: Hawai'i & Pacific Islands, KM 1).[62,63]

Key Message 2

Marine Resources

Marine ecological systems provide key ecosystem services such as commercial and recreational fisheries and coastal protection. These systems are threatened by changes in ocean surface temperature, ocean acidification, sea level rise, and changes in the frequency and intensity of storm events. Degradation of coral and other marine habitats can result in changes in the distribution of species that use these habitats and the loss of live coral cover, sponges, and other key species. These changes will likely disrupt valuable ecosystem services, producing subsequent effects on Caribbean island economies.

Linkage Between Climate Change and Regional Risks

Corals are a major component of the coastal protection, fisheries, and tourism economy of Caribbean islands. Key Message 3 discusses the importance of coastal systems to island economies and the potential effects of climate change on these economies. As in many tropical island systems, coral reefs anchor one end of the ridge-to-reef continuum—a concept that recognizes the linkage of social, ecological, terrestrial, and marine components associated with island systems (Ch. 27: Hawai'i & Pacific Islands). Recognizing that the coral reef ecosystem includes mangrove and seagrass habitats, this section briefly discusses the role these habitats play in fisheries and the potential impacts climate change is likely to have on this role.

Ocean warming poses significant threats to the survival of coral species and may also cause shifts in associated habitats that compose the coral reef ecosystem (Ch. 9: Oceans, KM 1 and 3).[35] The primary observable response to ocean warming is bleaching of adult coral colonies, wherein corals expel their symbiotic algae in response to stress. Severe, repeated, or prolonged periods of high temperatures leading to extended coral bleaching can result in colony death. Ocean warming can also harm hard corals that form coral reefs by decreasing successful sexual reproduction, causing abnormal development, impairing coral larvae's attempts to attach to and grow on hard substrate, and affecting hard corals' ability to create their calcium carbonate skeleton. Ocean warming also increases the susceptibility of corals to diseases and is expected to increase the impact of pathogens that cause disease.[64] In 2005, a mass bleaching event, driven by 12 weeks of temperatures above the normal local seasonal maximum, affected the entire Caribbean region, resulting in the loss of 40%–80% of the coral cover in the region.[65]

Ocean acidification associated with rises in carbon dioxide (CO_2) levels also is likely to diminish the structural integrity of coral habitats, affecting fisheries and other marine resources (Figure 20.9).[35] One study concluded that calcification rates have decreased by about 15% based on examination of different species of calcification in planktonic foraminifera.[66] Uncertainty remains about the magnitude of decreases in calcification on coral reefs and some crustaceans and mollusks (such as queen conch). However, a small decline in calcification rates has the potential to alter the growth–erosion balance of reefs if the erosion of the hard structure of reefs becomes more frequent.[67] Ocean acidification effects could be further exacerbated by local processes in coastal zones, such as land-based transport of nutrients to nearshore waters.

The compounded risk of climate change with human-caused stressors increases vulnerability and accelerates habitat loss and degradation.[68] Where fringing (nearshore) and barrier reef systems have eroded, mangroves and seagrass may also decline due to the loss of protection from wave action afforded by reefs. The potential decline in seagrass and mangrove habitats would be compounded by the effects of coastal and in-water development on these habitats and on coral reefs, resulting in overall declines in nursery habitat for important fishery species like spiny lobster, queen conch, snappers, and groupers. The impacts of climate change, in general, on seagrass in the Caribbean is uncertain, but some studies suggest that photosynthesis could be inhibited at high temperatures.[69] Sea level rise may lead to a reduction in the area occupied by seagrass if waters become too deep for the plants to obtain enough light to photosynthesize. Sea level rise is also projected to result in a loss of mangrove habitat if low-lying coastal areas are not present or have already been developed on islands such that mangroves cannot colonize these areas as coastal waters get deeper.[70] Additionally, increases in the magnitude and frequency of storms result in impacts caused not only by waves and surge but also by increased rainfall and the associated transport of sediment and other land-based pollutants into nearshore waters. Mangrove and seagrass habitats filter storm water runoff, but large volumes of sediment transported downstream can overwhelm these systems, leading to burial of seagrass beds and partial burial of mangrove roots, thus affecting the ability of these habitats to reduce pollutant transport to coral reefs.

Caribbean reefs have experienced declines in important fishery species—such as the Caribbean spiny lobster and queen conch; predatory species, such as snappers and groupers; and important herbivores, like parrotfish—due to overexploitation.[71,72] Overexploitation is demonstrated by the exceedance of commercial annual catch limits (established by the Caribbean Fishery Management Council to protect depleted stocks) in 2013 in Puerto Rico and the USVI and in 2014 in Puerto Rico, leading to the establishment of additional regulatory measures.[73] In terms of annual economies, commercial fishing of reef fish provides an average of $9 million to Puerto Rico, $2.4 million to St. Thomas and St. John, and $3 million to St. Croix (in 2014 dollars).[73]

Studies show that major shifts in fisheries distribution, coupled with structural and compositional changes in marine habitats such as coral reefs due to climate change, adversely affect food security, shoreline protection, and economies throughout the Caribbean.[5,69,74,75,76] In the U.S. Caribbean region, where fishery resources are shared with other Caribbean islands, competition for fisheries resources are likely to increase as stock distribution changes due to climate change (Ch. 16: International, KM 4). Figure 20.10 shows the connections

between climate change, marine habitats and species, and human communities. In the case of Puerto Rico, the coral reef ecosystems off the east coast of the main island (Fajardo area) and the islands of Culebra and Vieques were estimated as generating $192 million per year for recreation and tourism and $1 million in coastal protection services annually (in 2007 dollars, or $217 million and $1 million in 2015 dollars, respectively).[68] For the territory of USVI, reef-related tourism was estimated as generating $96 million per year, and coastal protection was estimated as providing $6 million annually to the local economy (in 2007 dollars, or $108 million and $7 million in 2015 dollars, respectively).[68`]

Climate Change Effects on Coral Reefs

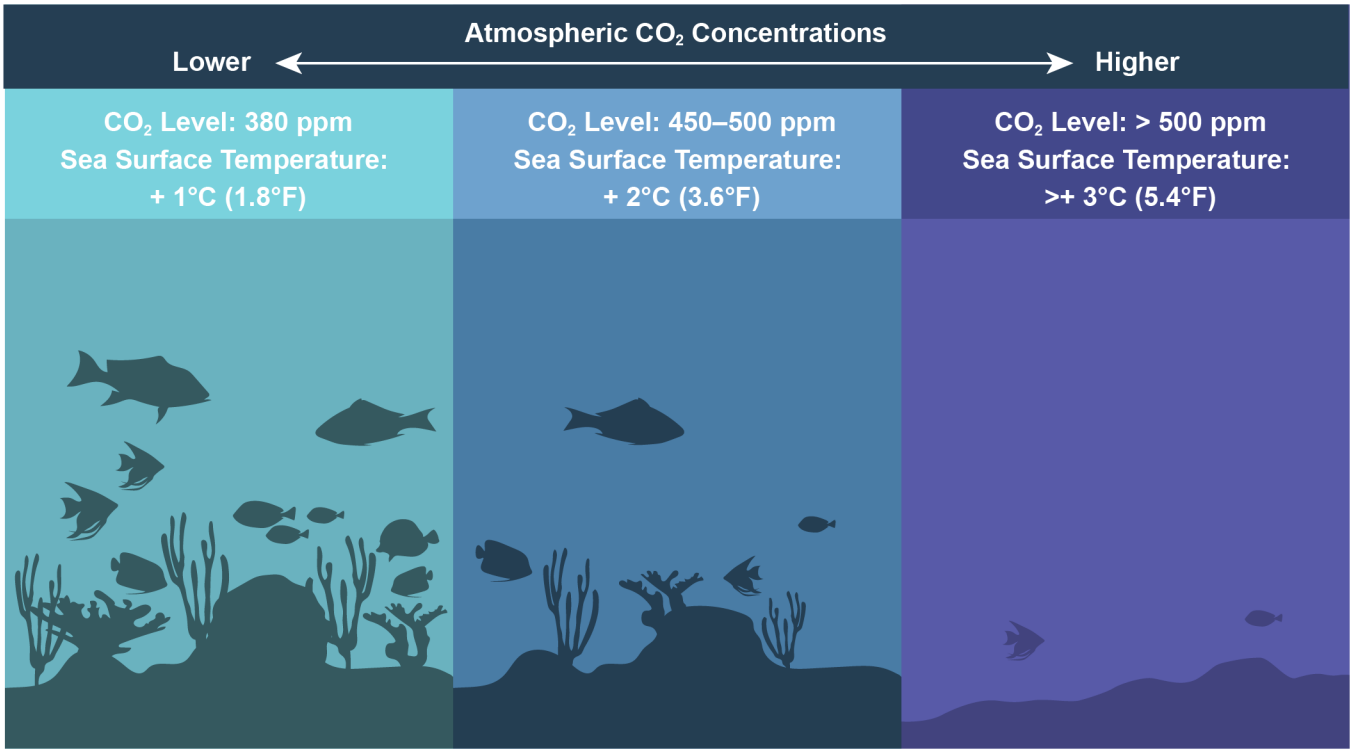


Figure 20.9: The diagram demonstrates how coral reef ecosystems in the U.S. Caribbean are likely to change in potentially warmer and more acidic waters caused by climate change, including elevated sea surface temperatures and elevated carbon dioxide (CO_2) levels. The severity of these impacts increases as CO_2 levels and sea surface temperatures rise. If conditions stabilized with concentrations of atmospheric CO_2 at 380 ppm (parts per million), coral would continue to be carbonate accreting, meaning reefs would still form and have corals. At 450–500 ppm, reef erosion could exceed calcification, meaning that reef structure is likely to erode and coral cover is likely to decline dramatically. Beyond 500 ppm, corals are not expected to survive.[77] Sources: NOAA and USFS.

Climate Change Impacts on Coral Reef Ecosystems and Societal Implications

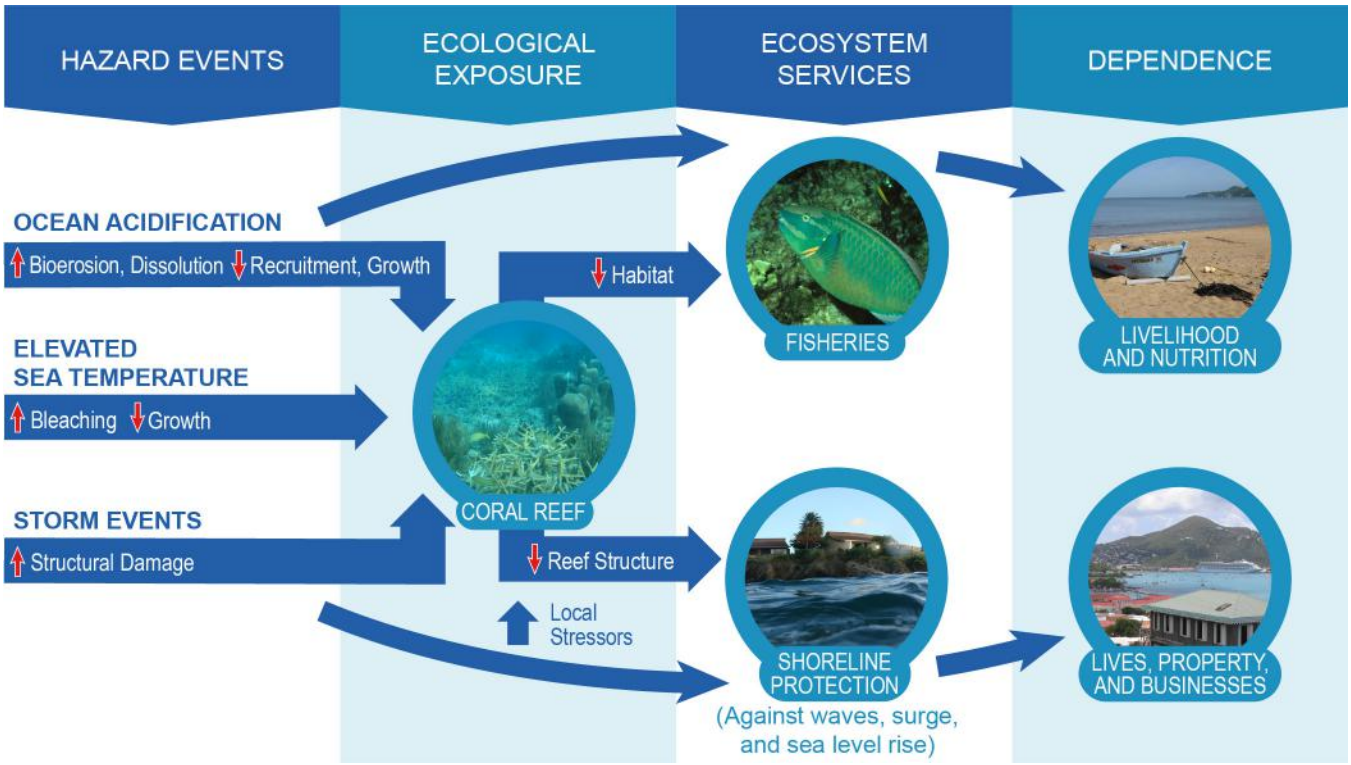


Figure 20.10: The figure shows the connections between climate-related impacts (ocean acidification and warming as well as severe storms), responses of marine habitats and species to these impacts, and, ultimately, the effects to ecosystem services (such as fisheries and shoreline protection) and, in turn, the human community. Specifically, the figure depicts how degradation of coral reefs due to climate change is expected to affect fisheries and the economies that depend on them as habitat is lost. The figure also shows how reef degradation decreases shoreline protection for local communities, which affects the economy and human populations more generally. Source: adapted from Pendleton et al. 2016.[78] Photo credits: NOAA.

Future Climate Change Relevant to Regional Risks

With high levels of greenhouse gas emissions (in other words, business as usual), mass coral bleaching in the Caribbean may occur at least twice a year within the next decade.[79] The increasing frequency of extreme heat events is highly likely to preclude reef recovery, considering that the region's reefs have yet to fully recover from the 2005 event. Moreover, the increase in average temperature will make corals more susceptible to extreme heat events and to coral disease, further contributing to declines in live coral cover in marine habitats.[64] One study suggests that coral reefs in Puerto Rico are expected to pass a critical ecosystem threshold in the first several decades of the century with coral cover loss of 95% by 2090 under a higher scenario (RCP8.5).[80]

Sea level rise is another climate-related stressor in the Caribbean. The rate of sea level rise in the region is expected to follow or exceed global projections. Sea level rise will likely have effects not only on marine communities by diminishing the amount of sunlight they receive but also on low-lying cays, which provide important habitat for seabirds and sea turtles. Coastlines on the larger islands and mainlands of the U.S. Caribbean will be submerged or greatly reduced in extent as sea levels rise. Coastal mangroves, squeezed between rising seas and coastal development, may be reduced in extent, diminishing the natural protection they provide against the action of

waves and storm surge and limiting their role as wildlife habitat. Sea level rise is also expected to lead to a loss of seagrass if waters become too deep for them to photosynthesize. Photosynthesis will also be inhibited as sea surface temperatures continue to rise, which is likely to affect both seagrass and mangroves in addition to corals, as noted above.

The combined stress of sea level rise, increases in sea surface temperatures, and ocean acidification, along with increases in the severity and frequency of storms and associated transport of land-based pollutants into coastal and marine habitats, will likely lead to loss and degradation of these habitats. Future climate change effects on marine habitats will likely impact island economies due to changes in the availability of key fishery species such as queen conch, Caribbean spiny lobster, and species in the snapper and grouper complexes; declines in natural shoreline protection and associated impacts to coastal infrastructure and communities, as well as wildlife habitat; and loss of tourism associated with habitats such as coral reefs. Fisheries productivity is projected to decline while catch-per-unit effort increases as fishers travel longer distances and spend more time on the water.[75] Potential losses of up to 90% of the coral reef recreation value in Puerto Rico are projected under most scenarios considered by the end of the century, due to the expected loss of coral reef habitat associated with climate change impacts.[80]

Challenges, Opportunities, and Success Stories for Reducing Risk

Climate change directly influences marine species' physiology, behavior, growth, reproductive capacity, mortality, and distribution, while indirectly influencing marine ecosystem productivity, structure, and composition.[74] As a result, fishery resources and essential habitats for commercially, recreationally, and ecologically important species are likely to be less resilient.

Several strategies meant to increase ecosystem resilience to local stressors (such as declines in water quality, overexploitation of fisheries, recreational use, and coastal and marine development) are being implemented in the Caribbean to lessen the potential impacts of climate change on marine resources. One such strategy is the establishment of protected areas in coastal and marine areas. Management of these areas may include limiting or prohibiting extractive uses, implementing conservation and restoration of coastal and marine habitats, and designating usage zones to minimize the impacts of recreational use on ecosystems. Another strategy is watershed planning to minimize the transport of land-based pollutants to nearshore waters, thus protecting marine habitats from declines in water quality caused by influxes of sediment, nutrients, and other contaminants. The NOAA Coral Reef Conservation Program, in partnership with federal and local agencies and local nongovernmental organizations, has sponsored the development and implementation of several watershed management plans in Puerto Rico and the USVI.[81]

Building the resilience of marine organisms, such as corals, is another strategy aimed at lessening the potential impacts of climate change on the marine ecosystem. Coral population enhancement through propagation (or coral farming) is a strategy meant to improve the reef community and ecosystem function, including for fish species that use this ecosystem (Figure 20.11). The selection and propagation of fragments and samples from coral colonies that have survived stressors such as bleaching events are emphasized as part of these efforts in an attempt to accelerate the otherwise uncertain recovery of these species.[82] This strategy has been used in the U.S. Caribbean and South Florida to recover species such as elkhorn and staghorn corals and species from the star coral complex—all of which are listed as threatened under the Endangered Species Act—without negatively affecting native populations of corals.

Coral Farming Can Increase the Extent and Diversity of Coral Reefs

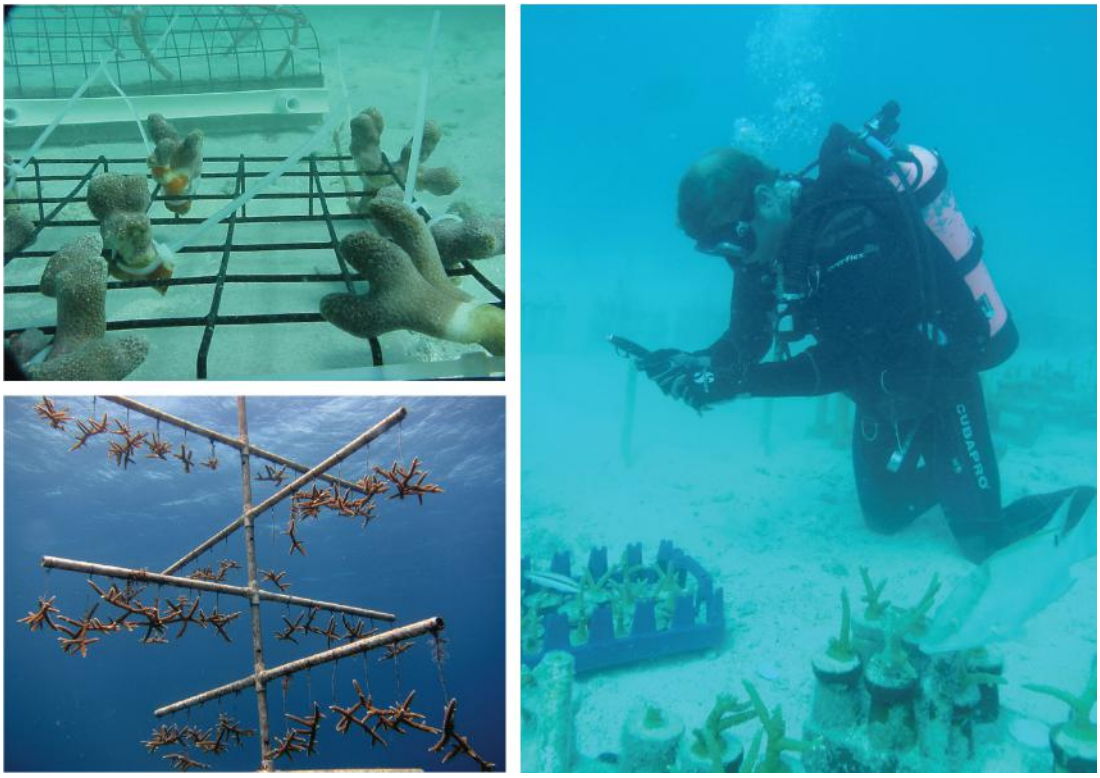


Figure 20.11: Examples of coral farming in the U.S. Caribbean and Florida demonstrate different types of structures used for growing fragments from branching corals. Coral farming is a strategy meant to improve the reef community and ecosystem function, including for fish species. The U.S Caribbean Islands, Florida, Hawai'i, and the U.S.-Affiliated Pacific Islands face similar threats from coral bleaching and mortality due to warming ocean surface waters and ocean acidification. Degradation of coral reefs is expected to negatively affect fisheries and the economies that depend on them as habitat is lost in both regions. While coral farming may provide some targeted recovery, current knowledge and efforts are not nearly advanced enough to compensate for projected losses from bleaching and acidification. Photo credits: (top left) Carlos Pacheco, USFWS; (bottom left) NOAA; (right) Florida Fish and Wildlife (CC BY-ND 2.0).

Emerging Issues

Integrating international monitoring networks of marine species and environmental conditions is critical to understanding the status and trends of wide-ranging marine resources. Areas like the Caribbean and the Pacific (Ch. 27: Hawai'i & Pacific Islands), where marine resources are key to socioeconomic well-being, benefit from monitoring programs that assess threats to reef health, ecosystem services, and reef-dependent communities. Research into the linkages between climate change and marine ecosystems is critical to enhancing the ability to predict future ecosystem responses to climate change and the associated socioeconomic consequences, as well as finding ways to mitigate those consequences.

Key Message 3

Coastal Systems

Coasts are a central feature of Caribbean island communities. Coastal zones dominate island economies and are home to critical infrastructure, public and private property, cultural heritage, and natural ecological systems. Sea level rise, combined with stronger wave action and higher storm surges, will worsen coastal flooding and increase coastal erosion, likely leading to diminished beach area, loss of storm surge barriers, decreased tourism, and negative effects on livelihoods and well-being. Adaptive planning and nature-based strategies, combined with active community participation and traditional knowledge, are beginning to be deployed to reduce the risks of a changing climate.

Linkage Between Climate Change and Regional Risks

A high concentration of population and critical infrastructure in low-lying coastal areas increases vulnerability to sea level rise and storm surge and magnifies the effects of coastal flooding and beach erosion. For example, most of the population in Puerto Rico (62%, or more than 2.2 million) lives in the 44 coastal municipalities, where a total of 1,019,300 housing units are also located.[83,84] It is also estimated that 401,145 people (11.5% of Puerto Rico's total population) live in areas subject to inundation, and 56,114 people live in areas susceptible to storm surge, also known as the coastal high hazard areas.[83] As sea level rises, storm surge and high energy wave action may cause shorelines to recede inland.[85] Approximately 60% of 3,808 beach transects studied along the coasts of Puerto Rico (799 miles) experienced erosion from the 1970s to 2010. Of those transects, 5% suffered very high erosion, with a beach loss of 3.97 feet to 6.56 feet per year.[86] Major loss of sand was identified in various municipalities of the north coast, including San Juan—the capital city and a center of economic activity, ports, and tourism—as well as Loíza and Dorado, which are cultural and tourist destinations. (For more information on effects from extremes and disaster events, see Key Message 5.)

The response of coastal systems to sea level rise is dependent on local natural and human factors.[87] Natural ecological systems can protect coastlines from erosion but can also be affected by sea level rise and other environmental changes. Coral reefs, mangroves, and sand dunes buffer coastlines from erosion and inundation, providing protective services. They reduce risk to people and infrastructure from wave damage and flooding. The coral reef–mangrove systems can reduce risk and provide fishery services if space is available for landward mangrove migration; however, this process can be hampered by coastal development. Beaches and coastal dunes provide wave energy dissipation and coastal asset protection yet are highly susceptible to wave action and erosion.

The U.S. Caribbean Economy

The U.S. Caribbean territories of Puerto Rico and the U.S. Virgin Islands have distinct differences in topography, language, population size, governance, natural and human resources, and economic capacity. However, both are highly dependent on natural and built coastal assets. Service-related industries account for more than 60% of the USVI's economy and cater to more than 570,000 tourists, as well as an additional 2.1 million cruise ship passengers who arrive to the island each year.[88] In 2013 in the USVI, tourists and cruise ship passengers spent $851 million and $381 million, respectively (in 2013 dollars; $877 and $392 million,

respectively, in 2015 dollars). Approximately 3.7 million people visited Puerto Rico in 2016 as tourists, and an additional 1.3 million people arrived via cruise ships. Tourist and cruise ship passenger expenditures amounted to $3.8 billion and $202 million, respectively (in 2016 dollars; $3.8 billion and $200 million, respectively, in 2015 dollars).[89]

Beaches, affected by sea level rise and erosion, are among the main tourist attractions; consequently, these revenues from tourism are at risk due to limitations of access and deterioration to the coastal landscape. In addition, residents' recreational activities will likely be disrupted, as about 63% of Puerto Rican residents enjoy recreational activities such as swimming, bathing, or sunbathing on the beach.[90]

Operations of Puerto Rico's ports, the Luis Muñoz Marín (LMM) international airport, and the city of San Juan are currently at risk from extreme weather and climate-related events and will likely be even more vulnerable under projected sea level rise scenarios (Figure 20.12). In 2016, 93% of all passengers entering Puerto Rico through airports did so through the LMM airport.[91] The U.S. Caribbean's economy is also tied to climate impacts on Florida ports, as raw material for industries, food, clothes, and essential goods are shipped from Jacksonville, Florida, to the San Juan port and Isla Verde airport. As such, Florida's infrastructure vulnerability also affects the U.S. Caribbean.

Critical Infrastructure at Risk, San Juan Metro Area

Figure 20.12: Puerto Rico's Luis Muñoz Marín (LMM) international airport is already at risk from extreme weather and climate-related events and is expected to become more vulnerable in the future as a result of continuing sea level rise. Photo credit: Ernesto Díaz, Puerto Rico Department of Natural and Environmental Resources.

Cultural Heritage

Cultural and historic sites in the U.S. Caribbean region are threatened by sea level rise and storm surge. In the USVI, two significant early prehistoric sites, the Aklis and Great Pond archaeological sites, are directly threatened by sea level rise.[92] In Puerto Rico, effects on cultural heritage resources at risk due to climate change include impaired access to coastal resources like fishing, degraded ecotourism attractions, and loss of public access to beaches.[93] One of Puerto Rico's most notable cultural sites, the San Juan National Historic Site (El Morro), faces challenges from climate change, including sea level rise and coastal erosion.[94]

Critical Infrastructure, Property, and Real Estate

Sea level rise will likely increase threats to private, commercial, and residential property, as well as associated service infrastructure. Over 8,000 structures in Puerto Rico's low-lying areas would be affected by an increase in sea level of 1.6 feet (0.5 m). A sea level increase of 6.5 feet (2 m) would affect more than 50,000 structures located along the coast, causing approximately $11.8 billion in losses (in 2017 dollars).[83]

Critical infrastructure in the region is vulnerable to the effects of sea level rise, storm surge, and flooding. As an example, if sea levels rise 6.5 feet (2 m), which could occur during this century under the Intermediate-High to Extreme scenarios,[38,95] Puerto Rico and the USVI are projected to lose 3.6% and 4.6% of total coastal land area, respectively. Were such a rise to take place, Puerto Rico's critical infrastructure near the coast would be negatively impacted, including drinking water pipelines and pump stations, sanitary pipelines and pump stations, one wastewater treatment plant, and six power plants and associated substations.[96] In the USVI, infrastructure and historical buildings in the inundation zone for sea level rise include the power plants on both St. Thomas and St. Croix; schools; housing communities; the towns of Charlotte Amalie, Christiansted, and Frederiksted; and pipelines for water and sewage.

Challenges, Opportunities, and Success Stories for Reducing Risk

In Puerto Rico, the Department of Natural and Environmental Resources (DNER) commissioned the development of five climate change community-based adaptation plans for selected coastal municipalities.[97] Through an active community participation process, which included surveys and participatory mapping, these plans evaluated the risks and vulnerabilities posed by climate change and developed recommendations and adaptation strategies that will serve as guidance for municipal governments, communities, and local businesses (Figure 20.13).[97]

The USVI has released a guidance document to promote resilient coastal and marine communities through Ecosystem-based Adaptation (EbA). EbA reduces risk through the protection and restoration of natural areas like mangroves, dunes, and wetlands. High-risk areas were identified through analysis of social vulnerability, risk exposure, and adaptive capacity. Eleven areas throughout the USVI were selected as optimal to implement EbA options, as they faced high-risk exposure, high sensitivity, and low adaptive capacity. When considering climate effects and adaptation in the Caribbean, traditional knowledge from those members of the community maintaining the most intimate relationships with the land and natural systems is key to the early stages of the planning process. Traditional fishing, subsistence agriculture, and plant harvesting practices may provide a better understanding of how Caribbean Indigenous knowledge systems have sustained generations in the past and can benefit future generations.[98]

Assessing Vulnerability with Communities

Figure 20.13: Culebra's Mayor and community members worked on the participatory maps to identify risks, important natural resources, infrastructure, and important services to the community in Culebra. This exercise allowed them to gather information about issues in the territory that are important to the community but not commonly reflected in maps. Photo credit: Vanessa Marrero, Puerto Rico Department of Natural and Environmental Resources.

Natural and nature-based shoreline responses are used as stabilization techniques against erosion and can provide habitat for coastal species. Wetlands, dunes, and mangroves experience less damage from severe storms and are more resilient than hardened shorelines, and they also provide multiple benefits such as habitat for fish and other living organisms, as well as support recreational and commercial activities.[88] Mangroves alone can help reduce wave energy, erosion, and damage caused by large storms.[99] The U.S. Fish and Wildlife Service and the Puerto Rico DNER have funded wetland and dune restoration projects at various sites along the coast of Puerto Rico as nonstructural solutions to reduce coastal flooding and beach erosion.

Emerging Issues

Adaptive planning and nature-based strategies are gaining increased attention in Puerto Rico, as they are more accessible to coastal communities and can be cost effective. Also, stabilization and excavation of vulnerable cultural sites throughout the USVI can serve to protect or salvage cultural resources from the effects of climate change.[92]

Key Message 4

Rising Temperatures

Natural and social systems adapt to the temperatures under which they evolve and operate. Changes to average and extreme temperatures have direct and indirect effects on organisms and strong interactions with hydrological cycles, resulting in a variety of impacts. Continued increases in average temperatures will likely lead to decreases in agricultural productivity, changes in habitats and wildlife distributions, and risks to human health, especially in vulnerable populations. As maximum and minimum temperatures increase, there are likely to be fewer cool nights and more frequent hot days, which will likely affect the quality of life in the U.S. Caribbean.

Linkage Between Climate Change and Regional Risks

Records from weather stations in Puerto Rico indicate that the annual number of days with temperatures above 90°F has increased over the last four and a half decades (Figure 20.14). A number of extreme temperature events occurred in Puerto Rico during the summers of 2012–2014, when most days exceeded 90°F. This period included the hottest months on record and the longest continuous period of days over 90°F.[11] Higher temperatures drive increased energy demand to cool buildings and indoor environments. San Juan's record heat episode in 2012 drove record-level energy consumption. During that time, stroke and cardiovascular disease were the primary causes of death due, in part, to the elevated summer temperatures in the municipalities of San Juan and Bayamón (Ch. 14: Human Health, KM 1).[11,12]

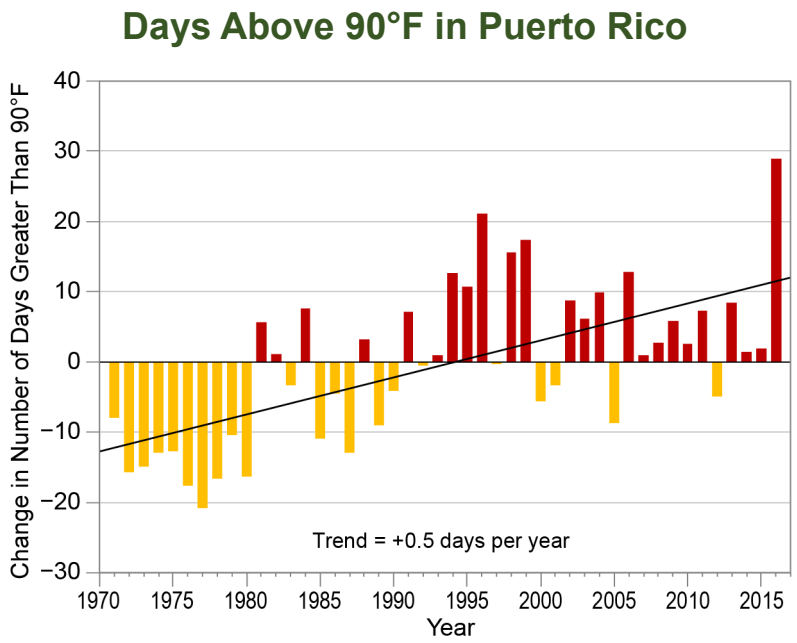


Figure 20.14: This figure illustrates the deviation from the long-term (1970–2016) average annual number of days exceeding 90°F, based on data from eight climate stations in Puerto Rico. Source: University of Puerto Rico.

Heat stress can exacerbate preexisting health conditions and lead to an increase in human mortality.[100,101] Time of year, repetition, duration, time between events, and adaptation of individuals are important determinants of the health outcomes during extreme heat episodes. Vulnerability to heat is a function of exposure and personal sensitivity, which depends on an array of individual factors and may influence the ability to cope with extreme temperatures.[102]

Urban areas are particularly vulnerable to extreme heat events, given the concentration of built structures, traffic, and other factors that drive the urban heat island (UHI) effect.[103,104] Since the middle of the last century, urbanization and population growth have increased the UHI effects in San Juan. Such effects are becoming even more life threatening with a growing and more vulnerable aging population. Heat vulnerability index maps show that the hottest and most vulnerable areas correspond to highly built areas, including within and around the LMM Airport, seaports, parking lots, and high-density residential areas, while cooler areas correspond to vegetated landscapes and urban bodies of water (such as lagoons and wetlands).[102]

The role of agriculture in Puerto Rico and the USVI is both economic and cultural. The economic role of agriculture has diminished in recent decades compared to the mid-20th century. Currently, less than 1% of Puerto Rico's gross domestic product (GDP) and approximately 1% of the USVI's GDP is due to agriculture.[13,89] Recent revitalizations in agricultural productivity are vulnerable to climate change. At risk are food security, rural livelihoods, and agroecological services. Increases in average temperature and extreme heat events will likely have detrimental effects on agricultural operations throughout the U.S. Caribbean region.[13,14] Climate change affects cattle ranchers and dairy farmers in the U.S. Caribbean by reducing productivity of rangeland, causing a shortage of nutritional feed, increasing heat stress on animals, and increasing energy costs for cooling.[105] High temperatures and resultant heat stress reduce animal productivity and increase the proliferation and survival of parasites and disease pathogens. Warming reduces the ability of dairy cattle to produce milk and gain weight and can lower conception rates.[105]

Tropical cropping systems are often more vulnerable to climatic shifts and anomalies for a number of reasons. Many farmers throughout the tropics, including in the U.S. Caribbean, are considered small-holding, limited resource farmers.[1,15] This terminology refers to farmers who own small parcels of land (fewer than 2–5 acres) and often lack the resources and/or capital to adapt to changing conditions.[15] Many important tropical crop species, such as coffee, evolved within relatively narrow temperature bands and are more sensitive to variation in rainfall and temperature than are crop species native to temperate regions.[24]

Finally, rising temperatures will generally increase regional sea surface temperatures, which tends to increase the maximum intensity that hurricanes in the region can achieve.[33] This can lead to stronger hurricanes and more active hurricane seasons in general, which the Caribbean region is especially vulnerable to, as evidenced by the 2017 hurricane season (see Box 20.1).

Future Climate Change Relevant to Regional Risks

Cooling degree days (CDDs), used as a proxy for future air conditioning energy demands, are projected to increase over time and to more than double in Puerto Rico by the end of century (Ch. 4: Energy, KM 1).[7] The warmer south coast is projected to have the highest increase in CDDs in the first half of the century, while

the San Juan metropolitan area is projected to have its highest increases in the second half of the century, suggesting higher energy demands in the island's largest metropolitan area by the end of the century.[7]

Warming, along with drying, is projected to affect the terrestrial ecosystems in the region. The ecological life zones of Puerto Rico are projected to shift from rain and wet zones to moist and dry zones based on the projected drying. By the middle of this century, under most scenarios considered, all life zones in Puerto Rico are projected to shift to tropical zones.[7] Environmental suitability for species in the region would be altered by life zone shifts, which may lead to biodiversity redistribution in the region. Environmental factors, especially climatic variables, were shown to have higher importance than land-use history on forest species composition in Puerto Rico and the USVI.[106] The projected changes in the amount and spatial variability of climatic variables will likely affect the composition and spatial redistribution of species.

Climate change adaptation strategies and national (as well as international) discussions and agreements have focused more on direct socioeconomic implications and less on changes in natural ecosystems; nonetheless, climate-induced species redistribution affects ecosystem functioning, human well-being, and the dynamics of the climate change itself and represents a substantial challenge for human society.[107] Species respond to changes in environmental conditions by tolerating the changes, adapting to the new conditions, facing extinction, or moving, which changes their distributions.[108] Warming forces species to move toward higher latitudes and altitudes.[109] On small islands in the Caribbean with limited latitudinal ranges, species' adaptive movement is limited to tracking changing temperatures toward higher altitudes.

Challenges, Opportunities, and Success Stories for Reducing Risk

Green and blue infrastructure are, respectively, the natural terrestrial vegetation and water-related components of an urban or other landscape. They provide many beneficial ecosystem services for surrounding microclimates.[102,110,111] Urban planning efforts in coastal cities are placing greater emphasis on the use of green infrastructure and water bodies for cooling urban environments. Planners in low-lying cities are also incorporating adaptable spaces that can accommodate occasional flood waters while providing services such as parks or urban open space[112] that can also help mitigate the UHI effect. In agriculture, the rapid expansion of electronic and worldwide communications is bringing old and new adaptation practices to a new generation of practitioners as they deal with multigenerational problems of water management and heat stress in crops and livestock.[13]

Emerging Issues

Cumulative effects on urban populations, agricultural sectors, and the natural environment add complexity to developing scenarios and prioritizing actions to reduce risks related to climate change. New alliances, collaborations, and governmental structures may be necessary to address these complex challenges.

Key Message 5

Disaster Risk Response to Extreme Events

Extreme events pose significant risks to life, property, and economy in the Caribbean, and some extreme events, such as flooding and droughts, are projected to increase in frequency and intensity. Increasing hurricane intensity and associated rainfall rates will likely affect human health and well-being, economic development, conservation, and agricultural productivity. Increased resilience will depend on collaboration and integrated planning, preparation, and responses across the region.

The Caribbean is highly vulnerable to disaster-related risks.[113] The U.S. Caribbean region experiences hurricanes, extreme rainfall, and droughts. The most extreme of these events have caused significant disruptions in Caribbean island livelihoods, including casualties and substantial economic losses. Current demographic and economic characteristics of Puerto Rico and the USVI—and their innate vulnerabilities as islands—result in greater sensitivity to these events, therefore imposing greater burdens in terms of response and recovery compared to many places in the continental United States.

Tropical cyclones (hurricanes and tropical storms), floods, and droughts are the most frequent and damaging extreme events in Puerto Rico. More than 50 extreme events related to floods, droughts, tropical storms, and winter swells have been declared emergencies and disasters since the mid-1990s.[114] Disaster declarations have occurred on a yearly basis since 2001.

Over the years, extreme events have caused billions of dollars in property and crop damages in Puerto Rico and the USVI. Tropical cyclones cause the most severe disruption and economic damage. In 2017, damages caused by Hurricanes Irma and Maria prompted a humanitarian crisis in the U.S. Caribbean by causing the collapse of the region's main energy, water, transport, and communication infrastructures (see Box 20.1). The estimated damages for Hurricane Maria alone totaled between $27 and $48 billion for the Caribbean region, with Puerto Rico estimates ranging from $25 to $43 billion (in 2017 dollars).[115] Total casualties caused by these hurricanes have proven difficult to establish. In Puerto Rico, estimates range from 64 to more than 1,000 deaths, although the evidence base is still evolving in this area.

Box 20.1: 2017 Atlantic Hurricane Season Impacts

The 2017 Atlantic hurricane season had devastating impacts across the Caribbean region (Figure 20.15) and reemphasized the exposure and vulnerabilities of the Small Island Developing States (SIDS) in the region.[116] During the unusually active 2017 hurricane season, there were 17 named storms (wind speeds of 39 mph or higher), 9 of which impacted one or more Caribbean SIDS. Twenty-two of the 29 Caribbean SIDS (including islands that are United Nation members and non–U.N. Associate Members of Regional Commissions) were impacted by at least one named storm, and a large number of SIDS experienced catastrophic impacts from major hurricanes (wind speeds of 111 mph or more). Five SIDS were impacted by three storms, 13 by two storms, and 4 by one storm. Eleven SIDS experienced tropical storm force winds (39 mph or higher wind speeds), 11 experienced hurricane force winds (74 mph or higher wind speeds), and 9 experienced direct landfall of a major hurricane.[116]

Of the 29 SIDS, only 7 were not significantly affected by the 2017 storms: Guyana, Jamaica, Suriname, Aruba, Bermuda, Cayman Islands, and Curaçao. Antigua and Barbuda, Cuba, Dominica, Saint Kitts and Nevis, Anguilla, British and U.S. Virgin Islands, Guadeloupe, Puerto Rico, Saint Maarten, and Turks and Caicos were all affected by Saffir–Simpson Category 4 and 5 hurricanes (winds of 130 mph or higher). The impacts and costs, in terms of lives and property damage, during the 2017 Atlantic hurricane season are still being calculated. In this age of satellite technology, hurricane warnings are generally timely, and mortality rates during local hurricane passage have been minimized, but post-event mortality numbers can grow quickly due to lack of electrical power, potable water, food, and access to adequate healthcare, among other factors (Ch. 14: Human Health, KM 1 and 2).[116,117] The death toll in Puerto Rico, for example, has been estimated to have grown by a factor of about 1700% in the three months following Maria's landfall on the island,[116] due in part to the lack of electricity and potable water, as well as access to medical facilities and medical care.

The health impacts across the Caribbean SIDS span a large range, including physical injury from wind and water during hurricane passage and during post-event rescue and cleanup efforts, heat-related injury due to loss of access to air conditioning and fans, inability to manage chronic disease due to loss of access to electrical power or medical services, and increased exposure to vector-borne diseases and diseases from contaminated water. Mental health impacts are also notable, as most survivors experience a high degree of psychological trauma during and after hurricane events (Ch. 14: Human Health, KM 1).[116]

Critical infrastructure in the region suffered catastrophic damages as a consequence of Hurricanes Irma and Maria. These hurricanes caused the complete failure of Puerto Rico's power grid[118] and the loss of power throughout the USVI. Telecommunication infrastructure suffered major damages in the aftermath of the 2017 hurricanes, severely disrupting the communication capabilities of both Puerto Rico and the USVI.[119] Over 70% of potable water infrastructure was also severely affected in Puerto Rico due to Hurricane Maria's impacts, primarily from direct damages to infrastructure and loss of electricity.[118]

Hurricanes Irma and Maria caused catastrophic damage to crops and infrastructure across farms in Puerto Rico and the USVI. In Puerto Rico, losses surpassed $2 billion in crops alone (in 2018 dollars), with damages to infrastructure adding much more to the total.[120] In the USVI, farms, ranches, and infrastructure, including government agriculture offices, experienced sizable damages; however, there are no official estimates of the economic value of the losses caused by the storms.

Box 20.1: 2017 Atlantic Hurricane Season Impacts, *continued*

Hurricane Maria caused severe damage to the milk and poultry industries in Puerto Rico. Over $4 million (in 2018 dollars) was lost in the poultry industry due to chicken mortality during the storm or conditions afterward (lack of water, shelter, or feed).[120] Similarly, many in the milk industry lost barns, food for cows, or power, leading to an inability to sustain operations.[121] Further, due to a lack of electricity, many residents were reluctant to purchase fresh chicken or milk, which affected the markets. Hundreds of thousands of residents are estimated to have left the islands in the aftermath of Hurricane Maria,[122] which is likely to affect the long-term demand for agricultural products.

Based on information in NOAA's ResponseLink, in the USVI, 479 vessels were displaced, and almost 4,000 orphaned containers, propane cylinders, marine batteries, and other waste from these vessels had to be removed from coastal waters after the hurricanes. In Puerto Rico, 376 vessels were displaced, and approximately 27,000 gallons of waste oil had to be recovered from these vessels and coastal waters after the hurricanes. Coral reefs and other marine habitats suffered impacts from transport of these vessels and associated debris into these habitats, as well as from debris transported in rivers and streams into nearshore waters. Hurricanes Irma and Maria also caused impacts to corals and other marine habitats due to bottom swells and wave action. Coral farms being used to grow Endangered Species Act–listed corals as part of reef restoration efforts were largely lost from sites around Puerto Rico and St. Croix, where they had been in place for years.

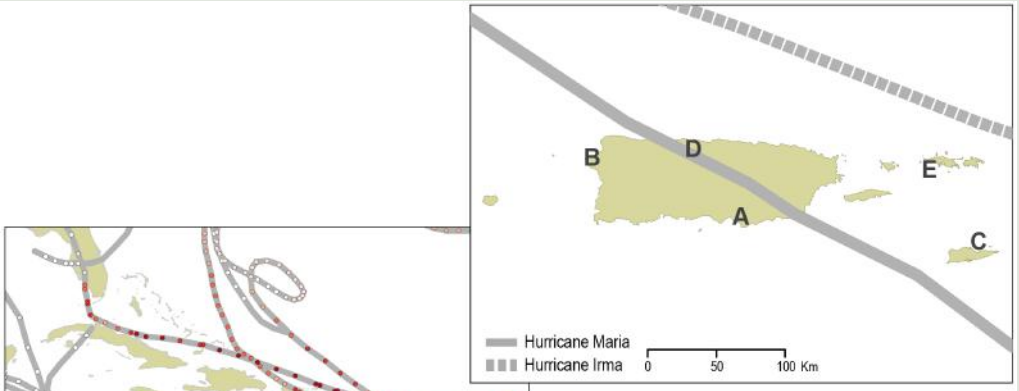
NOAA and its local and federal partners have been working on rapid assessments around the islands to determine the extent of damage to marine habitats in order to focus on habitat restoration and recovery efforts. Surveys in Puerto Rico from October to December 2017 looked at 30 high-value reef sites, of which 20 were identified as having moderate to major impacts needing emergency restoration. Damages included large coral heads being overturned or tossed into sand areas where they cannot grow successfully, extensive burial and breakage of corals from waves and storm surge, and physical impacts from grounded vessels and debris. Surveys in waters off Christiansted, St. Croix, found physical impacts to seagrass beds associated with barge and other vessel groundings due to Hurricane Maria. Whether marine habitats impacted by the hurricanes are left to recover naturally or experience some level of restoration, there are potential short-term impacts to ecosystem services such as fisheries and coastal protection while these habitats return to their pre-hurricane state.

The Caribbean lies in a region where the natural climate system acts in a way that compounds the effect that warm ocean temperatures have on hurricanes.[123] In particular, when ocean temperatures are unusually warm, other environmental factors that affect hurricanes tend to be optimized. This is not the case for regions along the U.S. mainland coast, where warmer waters tend to cause other factors to inhibit hurricanes.[124] There are also disparities between the United States' resources to respond to local hurricane impacts and those of the Caribbean SIDS. Furthermore, any impacts that may be exacerbated by global and regional climate change tend to disproportionately affect regions that are geographically small and relatively short on resources.[125]

The challenges of effective disaster response in the U.S. Caribbean region are daunting and formidable.[116] The 2017 Atlantic hurricane season provided a window into the vulnerabilities of the region and the difficulties in responding to hurricane impacts. As the response to the 2017 hurricane season continues in the region, sustained dialog among the range of stakeholders whose interests and areas of expertise are involved can improve strategies regarding response actions and coordination of response based on lessons learned in 2017 and 2018.

Box 20.1: 2017 Atlantic Hurricane Season Impacts, *continued*

Hurricane Impacts in 2017



Damage caused by hurricane winds to a storage facility in an orchard and fruit tree farm in Salinas.

Progressive erosion resulted in increased exposure to higher-energy wave action. Protection measures were not enough to withstand the force of Hurricane Maria–induced waves at Rincón, Puerto Rico.

Partially submerged sailboat grounded on Long Reef, St. Croix, during Hurricane Maria.

Severe flood conditions in La Charca, Florida, PR, where approximately 20 houses and a number of vehicles were affected by 10 feet of floodwater during Hurricane Maria.

Damage to Island Beachcomber Hotel from Hurricane Maria, Lindbergh Bay, St. Thomas.

Figure 20.15: In September 2017, the U.S. Caribbean region was impacted by two major hurricanes: Irma (Category 5) and Maria (Categories 4 and 5). This figure shows the hurricanes' tracks across both the Caribbean and (inset) the U.S. Caribbean region, as well as (A–E) some of the impacts felt throughout the region. Sources: (tropical cyclone tracks) NOAA NCEI and ERT, Inc. Photo credits: (A) Ricardo Burgos; (B) Ernesto Díaz, Puerto Rico DNER; (C) Michael Doig, NOAA; (D) Joel Figuero; (E) Greg Guannel, The University of the Virgin Islands.

Damages from Hurricanes Irma and Maria in Puerto Rico caused the longest-lasting power outage in U.S. history to date (Figure 20.16).[126] Communications for Puerto Rico and the USVI were largely disabled following the hurricanes, with a respective 88% and 69% of cellular communication infrastructure out of service.[119] For Puerto Rico, preliminary estimates suggest that economic losses to businesses due to wind damage for Hurricane Maria totaled $4.9 billion (in 2017 dollars, $4.8 billion in 2015 dollars).[127] Alongside economic loss and infrastructure damage, hurricane impacts also caused severe disturbances to terrestrial and marine ecosystems, including sensitive coral reef colonies in the region (see Box 20.1).

Historical events much less severe than those in 2017 have resulted in significant damages as well. In 1995, Hurricane Marilyn resulted in losses equivalent to 122% of the USVI's gross domestic product. From 2010 to 2016, hurricanes produced a loss of about $39 million (in 2015 dollars) to Puerto Rico's agricultural sector alone.

Over the past 20 years, floods in urban areas caused by extreme precipitation have frequently disrupted human and economic activities.[128] On July 18, 2013, a record 9 inches of rain fell in San Juan, Puerto Rico, in less than 24 hours,[129] affecting multiple residential and commercial areas. The resulting floods caused the temporary closure of the LMM International Airport, disrupting the movement of people and goods. In November 2016, heavy rains and associated flooding resulted in agricultural losses of approximately $13 million (in 2015 dollars) in Puerto Rico.[130]

Droughts are one of the most frequent climate hazards in the Caribbean. Since the 1950s, at least seven major droughts have occurred in the U.S. Caribbean.[131,132] Since 2000, there have been five moderate droughts in Puerto Rico that lasted, on average, 8.6 weeks (Figure 20.17). The most recent major regional drought of 2014–2016, classified as extreme, affected Puerto Rico and the USVI, as well as other islands in the region. At its peak, this drought covered more than 60% of Puerto Rico's land area.[133] Conditions resulted in water rationing for 1.2 million people and over $14 million in agricultural losses for 2015, primarily in livestock, grazing lands, bananas, and plantains.[40] While the onset and end of a drought are hard to determine, records of the U.S. Drought Monitor suggest that it takes only weeks of abnormally dry conditions before the declaration of a meteorological drought in Puerto Rico.[134]

Hurricane Maria Damage

Figure 20.16: Residential and vessel damages caused by Hurricane Maria in 2017, at (left) Palmas del Mar and (right) Punta Santiago, Humacao, Puerto Rico. Photo credits: (left) Ernesto Díaz, Puerto Rico DNER; (right) Vanessa Marrero, Puerto Rico DNER.

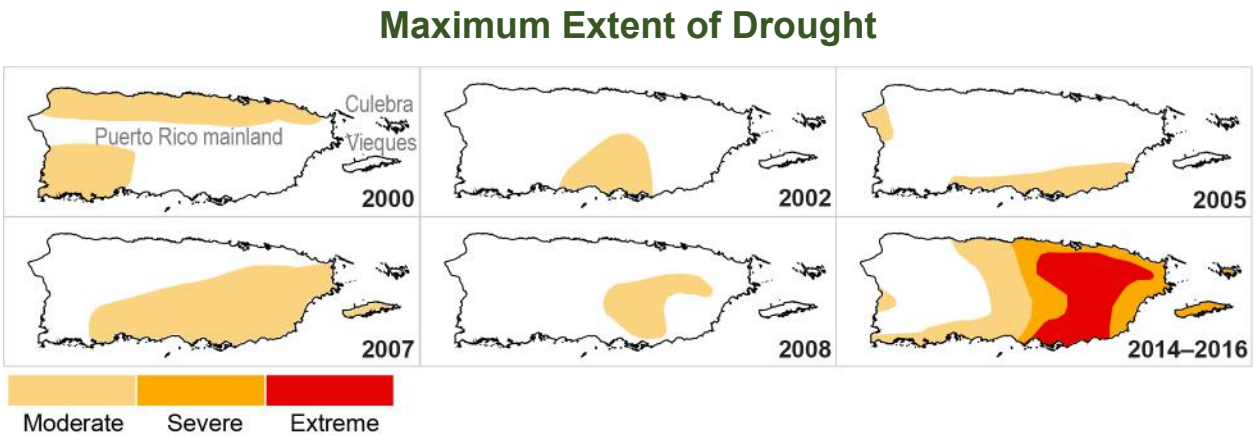


Figure 20.17: These maps show the maximum extent of each registered drought between 2000 and 2016 by the U.S. Drought Monitor. While six drought events were registered, the most severe of these occurred between 2014 and 2016, with extreme conditions covering the eastern half of the main island of Puerto Rico. The five events prior to 2014 were registered as moderate drought and were short-lived in comparison. Source: USDA Forest Service.

Future Climate Change Relevant to Regional Risks

While there is still much uncertainty in global climate model predictions of tropical cyclone formation,[135] climate models project an increase in the frequency of strong hurricanes (Categories 4 and 5) in the Atlantic Basin, including the Caribbean.[33] Drought projections for Puerto Rico suggest an increase in both drought intensity and frequency due to increases in both average and extreme temperatures and decreases in precipitation.[7]

Challenges, Opportunities, and Success Stories for Reducing Risk

The challenges for the U.S. Caribbean region in formulating disaster risk responses to extreme events lie in its geographical, social, and economic vulnerabilities. Puerto Rico and the USVI face common challenges, such as distance from continental resources, scarcity of land resources, increasing pressures on coastal and marine resources, high volume of food and fuel imports, and limited human resources.[1,25] Distance from the continental United States increases the region's vulnerability due to limited access to resources in times of need. Current fiscal and economic challenges of the region, coupled with an increasing elderly population, create additional challenges for the islands' governments to prepare for, respond to, and recover from climate-related disasters.

Improvements in data collection of extreme events and cost analyses of disasters have enhanced the resilience capacity of the U.S. Caribbean by supporting decision-making processes, particularly for drought events (see Box 20.4). Policymakers and disaster risk managers, as well as the general public, benefit from accurate data to support planning for disaster risk reduction. At present, current and historical data on the effects associated with extreme events are limited and not readily accessible for government officials and disaster risk managers.

Collaborative action has proven to be a successful strategy to manage and address the impacts from climate-related disasters.[136] Puerto Rico has actively provided humanitarian and technical support to other Caribbean nations and U.S. states during climate-related disasters and emergencies for at least 20 years. In Puerto Rico, collaborative actions among state and federal agencies, academics, and climate experts enabled improved preparation for and management of the 2014–2016 drought. Efficient coordination and collaboration among agencies prompted a largely effective

governmental response to the disaster risk reduction challenges, while also promoting greater public education and awareness about extreme events (see Box 20.4).

Key Message 6

Increasing Adaptive Capacity Through Regional Collaboration

Shared knowledge, collaborative research and monitoring, and sustainable institutional adaptive capacity can help support and speed up disaster recovery, reduce loss of life, enhance food security, and improve economic opportunity in the U.S. Caribbean. Increased regional cooperation and stronger partnerships in the Caribbean can expand the region's collective ability to achieve effective actions that build climate change resilience, reduce vulnerability to extreme events, and assist in recovery efforts.

Shared Risks and Opportunities

Caribbean countries and territories share broad similarities in characteristics related to climate vulnerability, including low availability of resources, high debt rates, coastal populations, remoteness, and dependence on imports and global markets.[137] The recent impacts of Hurricanes Irma and Maria in 2017 brought to light the high vulnerability of Caribbean islands to natural disasters and the potential benefits of adopting long-term resilience measures. Increased regional cooperation and strengthening partnerships between Puerto Rico, the USVI, and the wider Caribbean countries can be achieved through collaborative climate research; by performing regional assessments of vulnerabilities, risks, and mitigation potential via joint efforts in adaptation planning and education; and by designing early warning systems to support strategic decision-making. These efforts are likely to increase resilience and the adaptive capacity of Caribbean countries by leveraging capabilities and resources and may help to speed up disaster recovery, reduce the loss of life, enhance food security, and improve economic opportunity in the region. The period following climate-related disasters can provide the opportunity to reduce future risks, when political attention is heightened and key decisions are being made on response, recovery, and planning. Being proactive and building back better is a simple idea, but its implementation has diverse challenges.[138] Recovery is not a neat linear progression with a clear end point but is rather a part of an ongoing process of development and change with attendant uncertainties and hurdles, including financing, personnel, and incentives for collaboration across Caribbean islands.[16,138,139]

New and sustained cooperation mechanisms between U.S. territories and Caribbean countries would likely increase the participation of Puerto Rico and the USVI in regional initiatives addressing climate adaptation and disaster risk reduction.

Effectiveness of Cross-Regional Collaboration for Building Resilience

There is a history of regional efforts on climate change assessment and governance in the Caribbean (Figure 20.18). Joint regional efforts to address climate challenges include the implementation of adaptation measures to reduce natural, social, and economic vulnerabilities, as well as actions to reduce greenhouse gas emissions. The Caribbean Small Island Developing States (SIDS) have articulated national climate change adaptation policies and implementation plans using processes similar to the UN Framework Convention on Climate Change guidance for preparation of national adaptation programs of action.

Climate Research and Risk Management Organizations

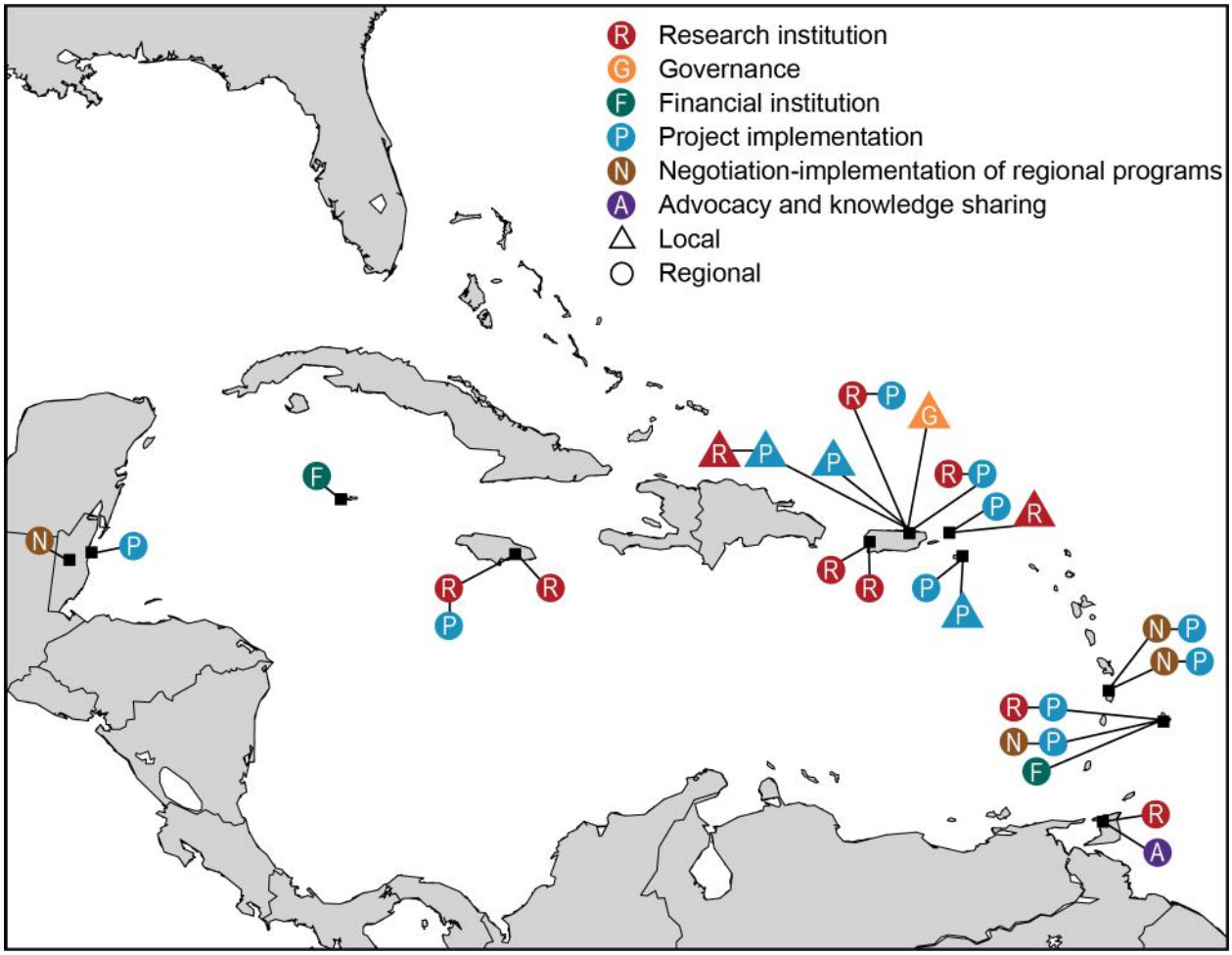


Figure 20.18: Some of the organizations working on climate risk assessment and management in the Caribbean are shown. Joint regional efforts to address climate challenges include the implementation of adaptation measures to reduce natural, social, and economic vulnerabilities, as well as actions to reduce greenhouse gas emissions. See the online version of this figure at http://nca2018.globalchange.gov/chapter/20#fig-20-18 for more details. Sources: NOAA and the USDA Caribbean Climate Hub.

Two regional entities specifically focused on developing and improving information, services, and planning to support climate risk management are the Caribbean Community Climate Change Centre (5Cs) and the Caribbean Institute for Meteorology and Hydrology (CIMH; see Boxes 20.2 and 20.3). The 5Cs is headquartered in Belize and is the main organization improving the framework and activities for addressing climate change in the Caribbean region.

The 5Cs projects include development and training in the use of analytical tools (for example, CCORAL; see Box 20.4), translating the outputs from global climate models for application at the scale of small islands, deployment of climate and coral reef monitoring equipment, provision of policy guidance for mainstreaming climate change considerations into regional development activities, preparation of a Regional Framework for Achieving Development Resilient to Climate Change[140] and its accompanying Implementation Plan, and the construction of desalination facilities powered by solar photovoltaic systems as solutions to water scarcity. The CIMH is an institution of the Caribbean Community (CARICOM) and is the technical arm of the Caribbean Meteorological Organization, a member of the UN World Meteorological Organization. The role of the CIMH is to assist in improving and developing

climate services and to provide awareness of the benefits of meteorology and hydrology for economic and environmental well-being. Both the 5Cs and CIMH have engaged with U.S. territories in anticipating and reducing risks and supporting adaptation actions.

Common to most Caribbean countries and territories are the needs to 1) assess risks; 2) enable people and actions at regional, national, and local scales; and 3) assess changes in ecosystems and species to inform decision-making on habitat protection under a changing climate (Ch. 28: Adaptation, Figure 28.1).[16,17] The CARICOM regional strategy and the framework for transformation are clear steps in that direction and encompass goals that are shared by Puerto Rico and the USVI.

Box 20.2: United States Virgin Islands and 5Cs Partnership on Vulnerability Assessment

The 5Cs, in conjunction with the National Oceanic and Atmospheric Administration (NOAA), developed a Vulnerability and Capacity Assessment Methodology inventory (Ch. 16: International, KM 4), which was used and modified under the European Union–Global Climate Alliance Programme (2011–2015) in several Caribbean countries. The 5Cs–NOAA method was combined with the approach derived from a local planning guidebook on preparing for climate change developed under the NOAA Regional Integrated Sciences and Assessments program.[141] This combined approach led to a Caribbean-specific methodology that has been successfully applied in Antigua and Barbuda, Saint Lucia, Saint Kitts and Nevis, and Grenada.[142,143] Common challenges across the region include relatively small islands with diverse microclimates, locations, and levels of exposure to climate-related risks; the expanse of human settlement and critical facilities located along vulnerable coastlines; inadequate forward planning; and a heavy dependence on imports of commodities, equipment, and energy, which leads to extreme vulnerability to external economic shocks (Ch. 16: International, KM 1). These best-case examples provide a template for the vulnerability assessment that is currently being executed in the USVI under the Climate Change Adaptation Planning Assessment and Implementation project.

Box 20.3: CIMH, NOAA, and the 5Cs Partnership to Deliver Climate Services

In 2010, CIMH, in partnership with NOAA and the 5Cs, reestablished the Caribbean Regional Climate Outlook Forum to serve as the convening mechanism for regional engagement, early warning information, climate impacts, and responses.[16] Products resulting from this include the Caribbean Regional Drought Monitor and Climate Impacts Report.[144,145] Based on successes in the Caribbean Regional Outlook Forum, CIMH is leading the multisectoral Consortium of Sectoral Early Warning Information Systems Across Climate Timescales (EWISACTs). The EWISACTs agreement makes the Caribbean the first region to formally create and implement a joint commitment between climate-sensitive sectors and a public climate services provider to support climate-resilient risk management and development.

Box 20.4: Collaboration and Tools for Cross-Country Capacity Building and Decision-Making

The Caribbean Climate Online Risk and Adaptation tooL (CCORAL) is a planning tool that can help countries make climate-resilient decisions and take actions in response to a changing climate. (http://www.caribbeanclimate.bz/caribbean-climate-chage-tools/tools/)

The **Caribbean Catastrophe Risk Insurance Facility** is the world's first index-based parametric insurance mechanism. It is a partnership of 17 Caribbean countries and the World Bank. (https://www.ccrif.org/)

The **Caribbean Challenge Initiative** was launched in 2008, with support of The Nature Conservancy. Puerto Rico and the USVI later joined participating governments committed to conserving at least 20% of their nearshore marine and coastal environments by 2020 and to ensuring that these areas are managed through a long-term finance structure. (http://caribbeanchallengeinitiative.org/)

Reducing Risks and Supporting Adaptation: Gaps, Opportunities, and Benefits

The U.S. Caribbean region has potential to improve adaptation and mitigation actions by fostering stronger collaborations with Caribbean initiatives on climate change and disaster risk reduction. The U.S. Caribbean islands are not members of CARICOM. However, the Government of Puerto Rico established a memorandum of understanding with the 5Cs to work collaboratively in climate adaptation and mitigation initiatives. Such agreements provide mechanisms to foster cooperation and build capacity in the region beyond the capabilities of any single island, leveraging greater support to address common challenges. U.S.-based centers and activities can benefit from and contribute to regional resilience. Key among these are the U.S. Department of Agriculture's Caribbean Climate Hub, the U.S. Department of the Interior's Climate Adaptation Science Centers, and NOAA's Caribbean initiative, which is supported by NOAA's Climate Program Office and NOAA's Office for Coastal Management.

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Traceable Accounts

Process Description

The majority of our Key Messages were developed over the course of two separate author meetings. The first occurred March 9–10, 2017, and the second on May 3, 2017. Both meetings were held in San Juan, Puerto Rico; however, people were also able to join remotely from Washington, DC, Raleigh, North Carolina, and the U.S. Virgin Islands (USVI). In addition, the author team held weekly conference calls and organized separate Key Message calls and meetings to review and draft information that was integral to our chapter. To develop the Key Messages, the team also deliberated with outside experts who are acknowledged as our technical contributors.

Key Message 1

Freshwater

Freshwater is critical to life throughout the Caribbean. Increasing global carbon emissions are projected to reduce average rainfall in this region by the end of the century (*likely, high confidence*), constraining freshwater availability, while extreme rainfall events, which can increase freshwater flooding impacts, are expected to increase in intensity (*likely, medium confidence*). Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers (*very likely, high confidence*). Increasing variability in rainfall events and increasing temperatures will likely alter the distribution of ecological life zones and exacerbate existing problems in water management, planning, and infrastructure capacity (*likely, medium confidence*).

Description of evidence base

The average global atmospheric carbon dioxide (CO_2) concentration has increased from 378 parts per million (ppm) in 2005 to over 406 ppm during April of 2017. The rate of increase over this period appears to be constant, and there is no indication that the rate will decrease in the future.[146] Several climate change studies have concluded that owing to increased atmospheric CO_2 and the consequent global climate change, rainfall will likely decrease in the region between now and the end of the century (e.g., Meehl et al. 2007, Biasutti et al. 2012, Campbell et al. 2011, Cashman et al. 2010[2,3,4,5]). Neelin et al. (2006)[147] and Scatena (1998)[148] have predicted increasingly severe droughts in the region in the future. Several downscaling studies, which specifically considered Puerto Rico, predict a reduction in rainfall by the end of the century[6,7,34] and constraints on freshwater availability. Furthermore, Taylor et al. (2018)[149] used the most recent generation of global climate models and demonstrated that when global warming increases from 1.5°C to 2°C above the preindustrial values (1861–1900), the Caribbean experiences a shift to predominantly drier conditions. Small watersheds that feed reservoirs are typical of the Caribbean region, and they are less able to serve as a buffer for rainfall variability. Small watersheds exhibit variable drainage patterns, which in turn affect evapotranspiration, groundwater infiltration, and surface water runoff. Drainage patterns in watersheds are also affected by the specific geometry, configuration, and orientation in relation to the average direction of wind over the region, as well as the morphology of rivers. With a projected reduction in rainfall up to 30% on average for the island by the end of the century,[7] certain watersheds will likely be less able to buffer rainfall variability and will likely see water

deficits in the near future. Increasing variability in rainfall events and increasing temperatures will likely exacerbate existing problems in water management, planning, and infrastructure capacity.

Streamflow is estimated using hydrologic models that are calibrated to networks of stream gauges and precipitation measurements. Reservoirs are considered in a permanent supply deficit if the annual streamflow leaving these reservoirs falls below zero after estimating withdrawals for human consumption, evapotranspiration, and rainfall. Projections of when deficit conditions could occur (circa 2025) are estimated using climate models.[46]

Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers. In Puerto Rico, groundwater quality can change when the water table is below sea level in coastal areas or when the intensity of pumping induces local upconing of deeper, poor-quality water.[43] Upconing is the process by which saline water underlying freshwater in an aquifer rises upward into the freshwater zone due to pumping.[150] When the water table is below sea level, the natural discharge of groundwater along the coast is reversed and can result in the inland movement of seawater or the upconing of low-quality water.[151,152] Diminished aquifer recharge and, to a lesser extent, increased groundwater withdrawals during 2012–2015 resulted in a reduction in the freshwater saturated thickness of the South Coast Aquifer. With sea level rise, groundwater quality will likely deteriorate even further in coastal aquifers in Puerto Rico.

Major uncertainties

As global changes continue to alter the hydrological cycle across the region, water resources are expected to be affected in both quantity and quality. There is still uncertainty as to the extent and severity of these global changes on small island nations such as Puerto Rico and the USVI, despite notable advancements in downscaled modeling exercises. Current climatological observations have presented an overall increase in mean annual precipitation across Puerto Rico.[153] However, climate model projections point toward an overall decrease in annual mean precipitation toward 2050 and an increase in rainfall intensity for extreme rainfall,[6,7,28,30,34,154] including rainfall associated with hurricanes. There is more uncertainty regarding the frequency and duration to changes in extreme rainfall within the region.[7,28,34]

Selected CMIP3 (Coupled Model Intercomparison Project, phase 3) and CMIP5 global climate models (GCMs) capture the general large-scale atmospheric circulation that controls seasonal rainfall patterns within the Caribbean[155] and provide justification that these GCM projections can be further downscaled to capture important rainfall characteristics associated with the islands.[156] Systemic dry biases exist, however, in the GCMs.[155] And many GCMs fail to capture the bimodal precipitation pattern in the region.[28] The CMIP3 generation of GCMs that do capture the bimodal rainfall pattern predict extreme drying at the middle and end of this century.[7,28] The CMIP5 generation of GCMs also projects drying by the middle and end of the century, but the magnitude of drying is not as large. Local and island-scale processes could affect these projected changes, since the land surface interacts with and affects both precipitation and evaporation rates.[157]

Description of confidence and likelihood

There is *high confidence* that freshwater availability will *likely* be constrained by the end of the century and *medium confidence* that extreme rainfall events will *likely* increase in intensity. There is *high confidence* that sea level rise will *very likely* cause saltwater intrusion impacts on coastal

freshwater aquifers. There is *medium confidence* about *likely* changes to ecological life zones but *low confidence* about the distributional effects on the existing terrestrial ecosystems in the region.

Key Message 2

Marine Resources

Marine ecological systems provide key ecosystem services such as commercial and recreational fisheries and coastal protection. These systems are threatened by changes in ocean surface temperature, ocean acidification, sea level rise, and changes in the frequency and intensity of storm events. Degradation of coral and other marine habitats can result in changes in the distribution of species that use these habitats and the loss of live coral cover, sponges, and other key species (*very likely, high confidence*). These changes will likely disrupt valuable ecosystem services, producing subsequent effects on Caribbean island economies (*likely, medium confidence*).

Description of evidence base

In 2006, the National Marine Fisheries Service (NMFS) listed elkhorn and staghorn corals as threatened species under the Endangered Species Act, with persistent elevated sea surface temperatures and sea level rise being two of the key factors influencing the listing decision.[158] The Acropora Biological Review Team (2005) found that the number of hurricanes affecting reef ecosystems in the Caribbean has increased over the past two decades (2 hurricanes in the 1970s, 6 in the 1980s, and 12 in the 1990s). Sea surface temperature is expected to continue rising, and this implies an increasing threat to elkhorn and staghorn corals from bleaching-induced mortality and possibly an exacerbation of disease effects. In 2014, NMFS listed an additional 5 species of Atlantic/Caribbean corals (lobed, mountainous star, boulder star, pillar, and rough cactus) as threatened and reevaluated the listing of elkhorn and staghorn corals, confirming them as threatened species; it also listed 15 Indo-Pacific coral species as threatened,[159] with two of the key factors being ocean warming and ocean acidification. Brainard et al.[159] found that ocean warming and related effects of climate change have already created a clear and present threat to many corals that will likely continue into the future and can be assessed with certainty out to 2100. Increases in human population densities and activity levels in the coastal zone are expected to continue, meaning the vulnerability of these populations and infrastructure will likely continue increasing with climate change.[160] Direct measurements at the Bermuda Atlantic Time-series Study station shows that surface ocean acidity has increased by about 12% and aragonite saturation (Ω_{arg}) has decreased by about 8% over the past three decades.[161] These values agreed with those reported across the Caribbean[162] and Atlantic regions[18,161] using regional and global numerical marine carbonate system models.

Many coastal regions already experience low surface seawater pH and Ω_{arg} conditions (localized or coastal ocean acidification) due to processes other than CO_2 uptake. As a result, the effect of ocean acidification on coastal zones can be several times higher and faster than typically expected for oceanic waters.[163]

Caribbean coral reefs in the Bahamas, Belize, Bonaire, and Grand Cayman are already experiencing significant reductions in carbonate production rates, with 37% of surveyed sites showing net erosion.[164] Friedrich et al. (2012).[66] concluded that calcification rates may have already dropped by about 15% within the Caribbean with respect to their preindustrial values.

Major uncertainties

The link between climate stressors such as increasing sea surface temperatures and bleaching response and increasing prevalence of disease in corals is postulated. There is some scientific evidence indicating a link, but it is hard to make definitive conclusions. Effects of climate change on fisheries in the Caribbean have not been as well studied as the effects on marine habitats, particularly coral reefs.[74,165] Similarly, the social consequences of climate change and associated declines in marine fisheries and the effects on coastal communities reliant on coral reef fishery species have not been as well studied.[166]

Uncertainty with respect to ocean acidification is dominated by uncertainty about how ecosystems and organisms will respond, particularly due to multiple interactions with other stressors.

The value of the loss of ecosystem services to ocean acidification is unknown. Such losses are attributable to the degradation of ecosystems that support important economic marine species such as coral, conch, oysters, fish larvae, urchins, and pelagic fish in the Caribbean. There is strong evidence for decreasing carbonate production, calcification rates, coral cover, and biomass of major reef-building species throughout the Caribbean region. However, there is still not enough evidence to conclude that all these decreased ecosystem processes are due to ocean acidification.

There are only a few studies on ecosystem and organism responses to climate stressors (such as ocean warming) that consider ocean acidification in the Caribbean. For instance, low pH values could affect nursery areas of commercially important species such as tuna, presenting a source of vulnerability for the economy, but studies are scarce. Ocean acidification could also affect the food web dynamics at lower trophic levels and have physiological effects at larval stages that would likely cascade upward, affecting coral and fish recruitment.

The effects of ocean acidification on coral reefs, shellfish, fish, and marine mammals will likely cause an economic effect on fisheries, coastal protection, and tourism in the Caribbean. Ocean acidification can exacerbate the current global warming effects on coral reefs, and it will likely continue deteriorating reef conditions and cause ecological regime shifts from coral to algal reefs.[77,167] The primary effect on reef communities will probably be a reduction in their capacity to recover from acute events such as thermal bleaching.

Sea level rise is currently the most immediate and well-understood climate-related threat to mangroves.[70] It is not clear how mangroves will respond to elevated CO_2, and some studies suggest increases may actually be beneficial to mangroves.[70] Similarly, in the Caribbean where temperatures are already high, increasing temperatures, as well as declines in rainfall and corresponding increases in soil salinity during periods of drought, will likely increase plant water stress and reduce productivity. There have been limited studies on the effects of climate change on seagrass beds; therefore, these effects remain uncertain.[69] Sea level rise that results in reduced sunlight due to increased water depths can lead to the loss of seagrass beds from deeper waters. As discussed previously, the loss or degradation of these habitats, which are part of the coral reef ecosystem

and serve as nursery habitat for important nursery species, will likely contribute to declines in fishery productivity due to climate change.

Description of confidence and likelihood

There is *high confidence* that increasing ocean temperatures, changes in ocean acidity, and changes in the frequency and intensity of storms are *extremely likely* to affect coastal and marine resources. Large storm events within the past decade have resulted in significant effects on marine resources, particularly coral habitats and organisms that rely on them. There is *medium confidence* in predictions that coral habitats will *likely* continue to decline throughout the Caribbean, with associated effects on resources dependent on these habitats; although, scientific studies are still needed in terms of climate change effects on fisheries resources, particularly for species that are found in offshore waters or are pelagic. Changes in coral habitats are already occurring as evidenced by massive coral bleaching events (including a three-year global-level bleaching event from 2015–2017) and the increase in these events. Such changes in bleaching events are due to rising sea surface temperatures. There is *high confidence* that there have been changes in ocean pH and *medium confidence* on the ecological effects. Due to the lack of studies on the social consequences of climate change and associated losses of resources such as fisheries, there is *medium confidence* that effects on coastal and marine resources resulting from climate change will affect island economies. These effects can be a result of changes in availability and condition of fishery resources, loss of reefs and other coral communities that serve as coastal barriers, and effects on tourism due to loss of the resources that are primary attractions for visitors.

There is *medium confidence* in the ecological effects that will result due to changes in ocean pH. The CO_2 system of seawater is well understood and established. As such, the understanding of the basic equilibria governing the process of ocean acidification dates back to at least 1960[168] and represents a foundational understanding of modern chemical oceanography. The ecological consequences of human-induced changes to the system (that is, ocean acidification) is, however, a considerably new field. Both themes were assessed considering recent findings and based on adequate observed local data (for example, atmospheric pCO_2 [carbon dioxide partial pressure] values are based on measurements of weekly air samples from St. Croix, the USVI, the United States, and Ragged Point, Barbados), complemented with empirical models. Projected changes in climate for the Caribbean islands were based on the future projections of fossil fuel emissions driven by reasonable models from the Intergovernmental Panel on Climate Change (IPCC).[169] Additional empirical species response data would be useful for increasing the understanding of expected effects of ocean acidification on species and habitats in the Caribbean.

Key Message 3

Coastal Systems

Coasts are a central feature of Caribbean island communities. Coastal zones dominate island economies and are home to critical infrastructure, public and private property, cultural heritage, and natural ecological systems. Sea level rise, combined with stronger wave action and higher storm surges, will worsen coastal flooding and increase coastal erosion (*very likely, very high confidence*), likely leading to diminished beach area (*likely, high confidence*), loss of storm surge barriers (*likely, high confidence*), decreased tourism (*likely, medium confidence*), and negative effects on livelihoods and well-being (*likely, medium confidence*). Adaptive planning and nature-based strategies, combined with active community participation and traditional knowledge, are beginning to be deployed to reduce the risks of a changing climate.

Description of evidence base

The Key Message and subsequent narrative text are based on the best available information for the U.S. Caribbean. There are not many studies on or projections for sea level rise for the U.S. Caribbean. Therefore, evidence of sea level rise used for this report comes from the U.S. Army Corps of Engineers' (USACE) Sea Level Change Curve Calculator.[95] To calculate the Intermediate and High scenarios, the USACE uses modified National Research Council (NRC) curves, the most recent IPCC projections, and modified NRC projections with local rate of vertical land movement.[95] The four NOAA estimates integrate data ranging from tide gauge records for the lowest scenario to projected ocean warming from the IPCC's global sea level rise projections combined with the maximum projection for glacier and ice sheet loss for 2100 for the highest scenario. The sea level rise analysis mainly focuses on data from two tide gauges chosen to be representative of the region, one in San Juan, Puerto Rico, and the other in Charlotte Amalie, USVI. There are two others in the region that provide sea level trend data located in Magueyes, Puerto Rico, and Lime Tree Bay, USVI.

Additional evidence that sea level is rising is well documented in Chapter 9: Oceans and in the *Climate Science Special Report*. There are also numerous empirical examples of sea level rise and its effects in Puerto Rico and the USVI, where beaches have been reduced by erosion, roads have been lost, and access to schools has been affected.

Major uncertainties

Sea level rise is already occurring. However, the uncertainty lies in how much of an increase will take place in the future and how coastal social and ecological systems will respond. There are various models and projections to estimate this number, but it is influenced by many unknown factors, such as the amount of future greenhouse gas emissions and how quickly glaciers and ice sheets melt. Another major uncertainty lies in humans' abilities to combat or adapt to these changes. The scale at which people and cities will be affected depends on the actions taken to reduce risk. Lastly, the experience of sea level rise on each coast and community is different, depending on land subsidence or accretion, land use, and erosion; thus, the severity of effects might differ based on these factors.

Due to the levels of uncertainty surrounding the projections, we focused much attention on the highest scenarios, as fewer consequences exist for planning in terms of the higher scenario (RCP8.5).

Description of confidence and likelihood

Sea levels have already risen and will likely continue to rise in the future. Based on current levels of greenhouse gas emissions, glacial melt, and ice sheet loss, there is *high confidence and likelihood* in these sea level rise projections.

Key Message 4

Rising Temperatures

Natural and social systems adapt to the temperatures under which they evolve and operate. Changes to average and extreme temperatures have direct and indirect effects on organisms and strong interactions with hydrological cycles, resulting in a variety of impacts. Continued increases in average temperatures will likely lead to decreases in agricultural productivity, changes in habitats and wildlife distributions, and risks to human health, especially in vulnerable populations. As maximum and minimum temperatures increase, there are likely to be fewer cool nights and more frequent hot days, which will likely affect the quality of life in the U.S. Caribbean. (*High Confidence*)

Description of evidence base

In warm tropical areas like Puerto Rico and the USVI, higher summertime temperatures mean more energy is needed to cool buildings and homes, increasing the demand for energy. Heat episodes are becoming more common worldwide, including in tropical regions like the U.S. Caribbean. Higher frequency, duration, and intensity of heat episodes are triggering serious public health issues in San Juan. Heat poses a greater threat to health and well-being in high-density urban areas. Land use and land cover have affected local climate directly and indirectly, facilitating the urban heat island (UHI) effect, with potential effects on heat-related morbidity and mortality among urban populations.

Major uncertainties

Warming is evident. A remaining scientific question is how ecological and social systems that have established themselves in a particular location can adapt to higher average temperatures.[170] Islands such as Puerto Rico are particularly vulnerable because of heat events associated with changes in both terrestrial and marine conditions. Although there is evidence suggesting that mortality relative to risk increases in San Juan due to extreme heat,[12] this association is not completely understood on tropical islands like Puerto Rico and the USVI. Addressing such hazards can benefit from new strategies that seek to determine linkages between human health, rapid and synoptic environmental monitoring, and the research that helps improve the forecast of hazardous conditions for particular human population segments or for other organisms.

Description of confidence and likelihood

There is *high confidence* that increasing temperatures threaten the health and well-being of people living in the U.S. Caribbean, especially in high-density urban areas where the UHI effect places further stress on city populations.

Key Message 5

Disaster Risk Response to Extreme Events

Extreme events pose significant risks to life, property, and economy in the Caribbean, and some extreme events, such as flooding and droughts, are projected to increase in frequency and intensity (*flooding as likely as not, medium confidence; droughts very likely, medium confidence*). Increasing hurricane intensity and associated rainfall rates (*likely, medium confidence*) will likely affect human health and well-being, economic development, conservation, and agricultural productivity. Increased resilience will depend on collaboration and integrated planning, preparation, and responses across the region (*high confidence*).

Description of evidence base

On both Puerto Rico and the USVI, disaster events have caused billions of dollars in property and crop damages.[171] Over the years, disaster-induced casualties have declined in both territories. Tropical cyclones, particularly hurricanes, continue to generate the most severe economic damage across the U.S. Caribbean. Floods and droughts are challenging to manage for both territories, and these challenges may be exacerbated by climate change induced shifts in precipitation regimes.

Climate modeling for tropical cyclone activity in the Atlantic Basin, including the Caribbean region, points toward an increase in the frequency of more intense hurricanes.[135] An increase in days with more than 3 inches of rain per 24-hour period is projected for Puerto Rico, based on statistically downscaled CMIP3 climate models.[28] Changes in precipitation patterns are expected for Puerto Rico in the periods 2030–2050 and 2100, pointing toward an overall decrease in mean precipitation for different climate change scenarios.[7,28,30,34]

While continental droughts typically affect vast regions, droughts affecting Puerto Rico and the USVI tend to vary significantly in extent and severity over smaller distances.[132] Statistically downscaled climate projections for Puerto Rico suggest an increase of drought intensity (measured as the total annual dry days) and extremes (measured as the annual maximum number of consecutive dry days) due to an increase in mean and extreme temperatures and a decrease in precipitation.[7]

An increase in mean atmospheric temperature has been observed across the U.S. Caribbean islands, particularly on Puerto Rico. An analysis of the observed temperatures across several NOAA weather stations in Puerto Rico showed rising temperature trends between 1970 and 2016.[172] Following the principles established by the international Expert Team on Climate Change Detection and Indices,[173] temperature extremes and trends were identified, indicating significant increases in rising annual temperatures and an increase in extreme heat episodes.

Major uncertainties

There are still uncertainties as to how these projected changes in tropical Atlantic cyclone activity will affect the frequency distribution of extreme precipitation events. While an increase in days with more than 3 inches of rain per 24-hour period has been projected based on statistically downscaled CMIP3 models,[28] more recent generations of GCMs do not show this increase in extreme rainfall events, and this adds uncertainty. Results from two dynamically downscaled climate models using the most recent generation of GCMs for the region do not show increases in the frequency of extreme events.[34]

At present, data pertaining to the costs and effects that are associated with extreme events and disasters are very limited and not readily accessible for government officials, disaster risk managers, or the general public. In the future, more accessible data could facilitate opportunities for more thorough analyses on the economic costs of extreme events for the U.S. Caribbean.

Description of confidence and likelihood

There is *high confidence* that increasing frequency of extreme events threatens life, property, and economy in the region, given that the U.S. Caribbean's vulnerable populations and fragile economies are continually exposed to climate extremes. There is *medium confidence* that the frequency and intensity of the most extreme hurricanes and droughts will likely increase. There is *high confidence* that extreme events will *likely* continue to affect human health and well-being, economic development and tourism, conservation, agriculture, and danger from flooding. There is *high confidence* that future recovery and cultural continuity will depend on significant and integrated resilience planning across the region, focusing on collaborative actions among stakeholders.

Key Message 6

Increasing Adaptive Capacity Through Regional Collaboration

Shared knowledge, collaborative research and monitoring, and sustainable institutional adaptive capacity can help support and speed up disaster recovery, reduce loss of life, enhance food security, and improve economic opportunity in the U.S. Caribbean. Increased regional cooperation and stronger partnerships in the Caribbean can expand the region's collective ability to achieve effective actions that build climate change resilience, reduce vulnerability to extreme events, and assist in recovery efforts (*very likely, high confidence*).

Description of evidence base

Cross-regional and international cooperation is a mechanism that will likely reduce climate vulnerability and risks in the U.S. Caribbean, because it builds capacity and leverages resources in a region that has low adaptive capacity, due in part to the high costs of mitigation and adaptation relative to gross domestic product.[1,17,145] There are several efforts among the islands focused on coordination, information exchange, and approaches for risk assessment and management in the Caribbean region.[142,143,144,145] There are emerging opportunities for improving these partnerships and capacity across the region.

Major uncertainties

There is high certainty that Caribbean island states are being affected by climate change, but the rate and degree of effects vary across countries due to the differences in environmental and socioeconomic conditions. Examples of regional cooperation efforts to share knowledge, conduct collaborative research, and develop joint projects have increased the adaptive capacity in the region; however, sustaining such efforts across the region remains a challenge. As efforts for regional coordination, cooperation, and information exchange evolve, evidence of the benefits of collaboration can be better assessed.

Description of confidence and likelihood

There is *high confidence* that climate change will *likely* result in serious water supply shortages and in increased risks for agriculture production, human health, wildlife, and the socioeconomic development of Puerto Rico, the USVI, and the wider Caribbean region. The effects of climate change in the Caribbean region are *likely* to increase threats to life and infrastructure from sea level rise and extreme events; reduce the availability of fresh water, particularly during the dry season; negatively affect coral reef ecosystems; and cause health problems due to high temperatures and an increase in diseases.

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21 Midwest

Carson, Wisconsin

Key Message 1

Agriculture

The Midwest is a major producer of a wide range of food and animal feed for national consumption and international trade. Increases in warm-season absolute humidity and precipitation have eroded soils, created favorable conditions for pests and pathogens, and degraded the quality of stored grain. Projected changes in precipitation, coupled with rising extreme temperatures before mid-century, will reduce Midwest agricultural productivity to levels of the 1980s without major technological advances.

Key Message 2

Forestry

Midwest forests provide numerous economic and ecological benefits, yet threats from a changing climate are interacting with existing stressors such as invasive species and pests to increase tree mortality and reduce forest productivity. Without adaptive actions, these interactions will result in the loss of economically and culturally important tree species such as paper birch and black ash and are expected to lead to the conversion of some forests to other forest types or even to non-forested ecosystems by the end of the century. Land managers are beginning to manage risk in forests by increasing diversity and selecting for tree species adapted to a range of projected conditions.

Key Message 3

Biodiversity and Ecosystems

The ecosystems of the Midwest support a diverse array of native species and provide people with essential services such as water purification, flood control, resource provision, crop pollination, and recreational opportunities. Species and ecosystems, including the important freshwater resources of the Great Lakes, are typically most at risk when climate stressors, like temperature increases, interact with land-use change, habitat loss, pollution, nutrient inputs, and nonnative invasive species. Restoration of natural systems, increases in the use of green infrastructure, and targeted conservation efforts, especially of wetland systems, can help protect people and nature from climate change impacts.

Key Message 4

Human Health

Climate change is expected to worsen existing health conditions and introduce new health threats by increasing the frequency and intensity of poor air quality days, extreme high temperature events, and heavy rainfalls; extending pollen seasons; and modifying the distribution of disease-carrying pests and insects. By mid-century, the region is projected to experience substantial, yet avoidable, loss of life, worsened health conditions, and economic impacts estimated in the billions of dollars as a result of these changes. Improved basic health services and increased public health measures—including surveillance and monitoring—can prevent or reduce these impacts.

Key Message 5

Transportation and Infrastructure

Storm water management systems, transportation networks, and other critical infrastructure are already experiencing impacts from changing precipitation patterns and elevated flood risks. Green infrastructure is reducing some of the negative impacts by using plants and open space to absorb storm water. The annual cost of adapting urban storm water systems to more frequent and severe storms is projected to exceed $500 million for the Midwest by the end of the century.

Key Message 6

Community Vulnerability and Adaptation

At-risk communities in the Midwest are becoming more vulnerable to climate change impacts such as flooding, drought, and increases in urban heat islands. Tribal nations are especially vulnerable because of their reliance on threatened natural resources for their cultural, subsistence, and economic needs. Integrating climate adaptation into planning processes offers an opportunity to better manage climate risks now. Developing knowledge for decision-making in cooperation with vulnerable communities and tribal nations will help to build adaptive capacity and increase resilience.

Executive Summary

The Midwest is home to over 60 million people, and its active economy represents 18% of the U.S. gross domestic product.[1] The region is probably best known for agricultural production. Increases in growing-season temperature in the Midwest are projected to be the largest contributing factor to declines in the productivity of U.S. agriculture.[2] Increases in humidity in spring through mid-century[3,4] are expected to increase rainfall, which will increase the potential for soil erosion[5,6] and further reduce planting-season workdays due to waterlogged soil.[7]

Forests are a defining characteristic of many landscapes within the Midwest, covering more than 91 million acres. However, a changing climate, including an increased frequency of late-growing-season drought conditions, is worsening the effects of invasive species, insect pests, and plant disease as trees experience periodic moisture stress. Impacts from human activities, such as logging, fire suppression, and agricultural expansion, have lowered the diversity of the Midwest's forests from the pre-Euro-American settlement period. Natural resource managers are taking steps to address these issues by increasing the diversity of trees and introducing species suitable for a changing climate.[8]

The Great Lakes play a central role in the Midwest and provide an abundant freshwater resource for water supplies, industry, shipping, fishing, and recreation, as well as a rich and diverse ecosystem. These important ecosystems are under stress from pollution, nutrient and sediment inputs from agricultural systems, and invasive species.[9,10] Lake surface temperatures are increasing,[11,12] lake ice cover is declining,[12,13,14] the seasonal stratification of temperatures in the lakes is occurring earlier in the year,[15] and summer evaporation rates are increasing.[13,16] Increasing storm impacts and declines in coastal water quality can put coastal communities at risk. While several coastal communities have expressed willingness to integrate climate action into planning efforts, access to useful climate information and limited human and financial resources constrain municipal action.

Land conversion, and a wide range of other stressors, has already greatly reduced biodiversity in many of the region's prairies, wetlands, forests, and freshwater systems. Species are already responding to changes that have

occurred over the last several decades,[17,18,19] and rapid climate change over the next century is expected to cause or further amplify stress in many species and ecological systems in the Midwest.[20,21,22] The loss of species and the degradation of ecosystems have the potential to reduce or eliminate essential ecological services such as flood control, water purification, and crop pollination, thus reducing the potential for society to successfully adapt to ongoing changes. However, understanding these relationships also highlights important climate adaptation strategies. For example, restoring systems like wetlands and forested floodplains and implementing agricultural best management strategies that increase vegetative cover (cover crops and riparian buffers) can help reduce flooding risks and protect water quality.[23,24,25]

Midwestern populations are already experiencing adverse health impacts from climate change, and these impacts are expected to worsen in the future.[26,27] In the absence of mitigation, ground-level ozone concentrations are projected to increase across most of the Midwest, resulting in an additional 200–550 premature deaths in the region per year by 2050.[28] Exposure to high temperatures impacts workers' health, safety, and productivity.[29] Currently, days over 100°F in Chicago are rare. However, they could become increasingly more common by late century in both the lower and higher scenarios (RCP4.5 and RCP8.5).

The Midwest also has vibrant manufacturing, retail, recreation/tourism, and service sectors. The region's highways, railroads, airports, and navigable rivers are major modes for commerce activity. Increasing precipitation, especially heavy rain events, has increased the overall flood risk, causing disruption to transportation and damage to property and infrastructure. Increasing use of green infrastructure (including nature-based approaches, such as wetland restoration, and innovations like permeable pavements) and better engineering practices are beginning to address these issues.

Conservation Practices Reduce Impact of Heavy Rains

Integrating strips of native prairie vegetation into row crops has been shown to reduce sediment and nutrient loss from fields, as well as improve biodiversity and the delivery of ecosystem services.[33] Iowa State University's STRIPS program is actively conducting research into this agricultural conservation practice.[34] The inset shows a close-up example of a prairie vegetation strip. *From Figure 21.2 (Photo credits: [main photo] Lynn Betts, [inset] Farnaz Kordbacheh)*.

Citizens and stakeholders value their health and the well-being of their communities—all of which are at risk from increased flooding, increased heat, and lower air and water quality under a changing climate.[30,31] To better prevent and respond to these impacts, scholars and practitioners highlight the need to engage in risk-driven approaches that not only focus on assessing vulnerabilities but also include effective planning and implementation of adaptation options.[32]

The photo shows Menominee Tribal Enterprises staff creating opportunity from adversity by replanting a forest opening caused by oak wilt disease with a diverse array of tree and understory plant species that are expected to fare better under future climate conditions. *From Figure 21.4 (Photo credit: Kristen Schmitt)*.

Background

The Midwest is home to more than 60 million people, and its active economy represents 18% of the U.S. gross domestic product.[1] In this report, the Midwest covers Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin. The region is probably best known for agricultural production. Trends toward warmer, wetter, and more humid conditions provide challenges for field work, increase disease and pest pressure, and reduce yields to an extent that these challenges can be only partially overcome by technology.[35] The Midwest contains large tracts of federal, state, and private forests and preserves that provide significant economic and ecological benefits to the region. However, as a changing climate results in shifting precipitation patterns, altered disturbance regimes, and increased frequency of late-growing-season moisture stress, the effects of existing stressors such as invasive species, insect pests, and plant disease are amplified.[36] Natural resource managers are taking steps to address these issues by increasing the diversity of trees and introducing species suitable for a changing climate.[8]

The Midwest also has vibrant manufacturing, retail, recreation/tourism, and service sectors. The region's highways, railroads, airports, and navigable rivers are major modes for commercial activity. Increasing precipitation, especially heavy rain events, has increased the overall flood risk, causing disruption to transportation and damage to property and infrastructure (e.g., Winters et al. 2015[37]). Increasing use of green infrastructure (including nature-based approaches, such as wetland restoration, and innovations like permeable pavements) and better engineering practices are beginning to address these issues (e.g., City of Chicago 2015[38]).

Tourism and outdoor recreation are major economic activities that may be affected by climate change, particularly in coastal towns that are at risk from algal bloom impacts and in areas that host winter sports that are especially vulnerable to warming winters. For example, ice fishing was limited due to mild temperatures in the winters of 2015–2016 and 2016–2017, and the American Birkebeiner cross-country ski race in Wisconsin was cancelled due to a lack of snow in February 2017. Portions of Michigan, Wisconsin, and Minnesota contain ceded territory of many tribes, and these are used for hunting, fishing, and gathering native plants, all of which play vital roles in maintaining cultural heritage. Projected changes in climate and ecosystems will have strong impacts on these activities.[39]

The Great Lakes play a central role in the Midwest and provide an abundant freshwater resource for water supplies, industry, shipping, fishing, and recreation, as well as a rich and diverse ecosystem. The same can be said for the upper Mississippi, lower Missouri, Illinois, and Ohio River systems. Episodes of widespread heavy rains in recent years have led to flooding, soil erosion, and water quality issues from nutrient runoff into those systems.[10] Land managers are beginning to change some of their practices (such as increasing the use of cover crops) to better manage excess surface water.[40]

Citizens and stakeholders in the Midwest value their health and the well-being of their communities—all of which are at risk from increased flooding, increased heat, and lower air and water quality under a changing climate.[30,31]

Energy in the Midwest

The Midwest is a major consumer of coal. In 2015, coal provided 56% of the electricity consumed in the region, and the eight states in the region accounted for 32% of the Nation's coal consumption (in BTUs). Coal's share of electricity production is declining in the Midwest, following the national trend (Ch. 4: Energy, Figure 4.3). In 2008, coal accounted for more than 70% of electricity consumption in the Midwest. Wind power is a small but growing source of electricity for the region. Iowa leads the Nation in per capita consumption of wind power, with wind providing over 30% of the state's electrical needs in 2015.[41]

Renewable energy is expanding in the Midwest. As part of a campus-wide initiative to transition to renewable energy sources, in 2017, Michigan State University established five solar carports that have an estimated annual production of 15,000 megawatt hours, representing about 5% of electricity use on campus (Figure 21.1). In addition to reducing carbon emissions, this investment is expected to save the university $10 million over 25 years.[42]

Solar Charging Stations

Figure 21.1: Solar carports were recently installed on the Michigan State University campus. Photo credit: David Rothstein.

What Is New in NCA4

Two new Key Messages are introduced (Key Messages 3 and 6). Key Message 3 recognizes the important role that ecosystems of the Midwest play in supporting a diverse array of species and providing important benefits such as flood control, crop pollination, and outdoor recreation. Key Message 6 addresses how at-risk communities in the Midwest are becoming more vulnerable to climate change impacts and how they are working to build adaptive capacity. Tribal nations are especially vulnerable because of their reliance on threatened natural resources for their cultural, subsistence, and economic needs. The four remaining Key Messages address improvements in the understanding of risks and responses to climate change since NCA3. Key Message 1 on agriculture provides more specificity about the risk to agriculture by stating that agricultural productivity (the ratio of outputs to inputs) is projected to decline by 2050 to levels of the 1980s (that is, yields may increase but at the cost of substantial increases in inputs). Key Message 2 on forestry illustrates the progress foresters and land managers have made in climate adaptation through their efforts to incorporate climate change risks into management decision-making. Key Message 5 on transportation and infrastructure highlights a growing interest in green infrastructure—the use of plants and open space in storm water management—as an option for adapting to more frequent episodes of extreme precipitation. Finally, Key Message 4 on human health identifies specific health impacts by naming expected changes in magnitude and occurrence of extreme events, exposures, and economic impacts. The message explicitly states public health actions that can be implemented to avoid or reduce the health impacts.

Key Message 1

Agriculture

The Midwest is a major producer of a wide range of food and animal feed for national consumption and international trade. Increases in warm-season absolute humidity and precipitation have eroded soils, created favorable conditions for pests and pathogens, and degraded the quality of stored grain. Projected changes in precipitation, coupled with rising extreme temperatures before mid-century, will reduce Midwest agricultural productivity to levels of the 1980s without major technological advances.

Recent Agriculturally Important Trends

The two main commodity crops in the Midwest are corn and soybeans, which are grown on 75% of the arable land. Wheat and oats are important crops grown on fewer acres. An increasing number of niche but higher-value crops (such as apples, grapes, cherries, cranberries, blueberries, and pumpkins) also are grown in the region.[43]

Over the past 30 years, increased rainfall from April to June has been the most impactful climate trend for agriculture in the Midwest,[3] providing a favorable supply of soil moisture while also reducing flexibility for timing of spring planting and increasing soil erosion.[44] In addition, wet conditions at the end of the growing season can create elevated levels of mold, fungus, and toxins.[45] The last spring frost has occurred earlier, causing the frost-free season to increase by an average of nine days since 1901.[46] However, daily maximum temperatures in summer in the Midwest have not followed the upward global trend, in part due to higher early summer rainfall on deep, water-holding soils,[47] thereby avoiding plant stress detrimental to crops. The avoidance of heat stress and longer growing seasons have favored production in some parts of and some years in the Midwest.

Daily minimum temperatures have increased in all seasons due to increasing humidity.[48,49] Elevated growing-season minimum daily temperatures are considered a factor in reducing grain weight in corn due to increased nighttime plant respiration.[50] Warming winters have increased the survival and reproduction of existing insect pests[51] and already are enabling a northward range expansion of new insect pests and crop pathogens into the Midwest.[52]

A contributing factor underpinning Midwest growing-season trends in both temperature and precipitation is the increase in water vapor (absolute humidity):[49,53] higher humidity decreases the day–night temperature range and increases warm-season precipitation. Rising humidity also leads to longer dew periods and high moisture conditions that favor many agricultural pests and pathogens for both growing plants and stored grain.

Projected Trends and Agricultural Impacts

Warm-season temperatures are projected to increase more in the Midwest than any other region of the United States.[54] The frost-free season is projected to increase 10 days by early this century (2016–2045), 20 days by mid-century (2036–2065), and possibly a month by late century (2070–2099) compared to the period 1976–2005 according to the higher scenario (RCP8.5).[46]

By the middle of this century (2036–2065), 1 year out of 10 is projected to have a 5-day period that is an average of 13°F warmer than a comparable period at the end of last century (1976–2005).[54] Current average annual 5-day maximum temperature values range from about 88°F in Northern Minnesota to 97°F in Southern Missouri. Tables 21.1 and 21.2 show

that by mid-century under the higher scenario (RCP8.5), 5-day maximum temperatures are projected to have moved further above optimum conditions for many crops and closer to the reproductive failure temperature, especially for corn in the southern half of the Midwest. Higher growing-season temperatures also shorten phenological stages in crops (for example, the grain fill period for corn).[35,50] Under these temperatures, overall yield trends will be reduced because of periodic pollination failures and reduced grain fill during other years.

Increases in humidity in spring through mid-century[3,4] are expected to increase rainfall, which will increase the potential for soil erosion[5,6] and further reduce planting-season workdays due to waterlogged soil.[7] As an example, for the Cedar River Basin in Iowa, the 100-year flood (1% chance of occurring in a given year) of the 20th century is projected to be a 25-year flood (4% chance per year) in the 21st century,[55] with associated increased frequency of flooding of agricultural land.

Increased spring precipitation and higher temperatures and humidity are expected to increase the number and intensity of fungus and disease outbreaks[56,57] and the prevalence of bacterial plant diseases,[58] such as bacterial spot in pumpkin and squash.[59] Increased precipitation and soil moisture in a warmer climate also lead to increased loss of soil carbon[60] and degraded surface water quality due to loss of soil particles and nutrients.[61,62] Transitions from extremes of drought to floods, in particular, increase nitrogen levels in rivers[63] and lead to harmful algal blooms.

Current understanding of drought in the Midwest is that human activity has not been a major component in historical droughts, and it remains uncertain how droughts will behave in the future. However, future projections show that Midwest surface soil moisture likely will transition from excessive levels in spring due to increased precipitation to insufficient levels in summer driven by higher temperatures, causing more moisture to be lost through evaporation.[64]

Average Annual 5-Day Maximum Temperature

Geographic Area	Modeled Historical (1976–2005)	Mid-21st Century (2036–2065) for Lower Scenario (RCP4.5)	Mid-21st Century (2036–2065) for Higher Scenario (RCP8.5)
Northern Minnesota	88°F	93°F	95°F
Southern Missouri	97°F	102°F	103°F

Table 21.1: These modeled historical and projected average annual 5-day maximum temperatures illustrate the temperature increases projected for the middle of this century across the Midwest. Sources: NOAA NCEI and CICS-NC.

Optimum and Failure Temperatures for Vegetative Growth and Reproduction

Crop	Optimum Growth	Failure for Growth	Optimum Reproduction	Failure for Reproduction
Corn	80°F	105°F	67°F	95°F
Soybean	86°F	101°F	72°F	102°F

Table 21.2: This table shows the temperatures at which corn and soybeans reach optimum growth and reproduction as well as the temperatures at which growth and reproduction fail.[50]

Projections of mid-century yields of commodity crops[65,66] show declines of 5% to over 25% below extrapolated trends broadly across the region for corn (also known as maize) and more than 25% for soybeans in the southern half of the region, with possible increases in yield in the northern half of the region. Increases in growing-season temperature in the Midwest are projected to be the largest contributing factor to declines in the productivity of U.S. agriculture.[2] In particular, heat stress in maize during the reproductive period is projected by crop models to reduce yields in the second half of the 21st century.[67] These losses may be mitigated by enhanced photosynthesis and reduced crop water use, although the magnitude is uncertain.[68,69] Elevated atmospheric CO_2 is expected to partially, but not completely, offset yield declines caused by climate extremes, with effects on soybeans less than on maize.[70]

Non-commodity crops produced in the Midwest include tree fruits, sweet corn, and vegetables for farmers markets and canning. While the general impacts of climate change on specialty crops are similar to commodity crops, the more intense heat waves, excessive rain interspersed with drought, and higher humidity of a future climate likely will degrade market quality as well as yield by mid-century.[71] Although data on climate-related losses are sparse, excess moisture is emerging as a major cause of crop loss.[72] Wild rice is an annual plant harvested by tribes and others in shallow wetlands of northern Minnesota, Wisconsin, and Michigan. Stable production depends on a stable climate that maintains ecosystem diversity. Declines in production are expected, related to increases in climate extremes and climate-related disease and pest outbreaks as well as northward shifts of favorable growing regions.[73]

Longer growing seasons and the introduction of hoop buildings (low, translucent, fabric-covered structures that protect plants from extreme weather) have allowed local growers of annual vegetable crops to extend the fresh produce season. However, unsheltered perennial crops such as tree fruits may be subjected increasingly to untimely budbreak followed by cold pulses due to earlier and longer occurrences of warm conditions in late winter.

Most animal agriculture in the region is in confinement, rather than range-based without shelter, and therefore offers an opportunity for mitigating some of the effects of climate change. Without adaptive actions, breeding success and production of milk and eggs will be reduced due to projected temperature extremes by mid-century.[74,75,76]

Adaptation

Soil-erosion suppression methods in row-crop agriculture subjected to more intense rains include use of cover crops, grassed waterways, water management systems, contour farming, and prairie strips.[6,40] More diversity in planting dates, pollination periods, chemical use, and crop and cultivar selection reduces vulnerability of overall production to specific climate extremes or the changes in pests and pathogens that they cause.

An example of a highly successful program is the Iowa State Science-based Trials of Rowcrops Integrated with Prairie Strips (STRIPS) program that demonstrates that replacing 10 percent of cropland with prairie grasses reduced sediment loss 20-fold while total nitrogen concentrations were 3.3 times lower (Figure 21.2).[33] An example of a private–public response is the National Corn Growers Association's Soil Health Partnership (SHP),[77] a network of working farms across the Midwest

Conservation Practices Reduce Impact of Heavy Rains

Figure 21.2: Integrating strips of native prairie vegetation into row crops has been shown to reduce sediment and nutrient loss from fields, as well as improve biodiversity and the delivery of ecosystem services.[33] Iowa State University's STRIPS program is actively conducting research into this agricultural conservation practice.[34] The inset shows a close-up example of a prairie vegetation strip. Photo credits: (main photo) Lynn Betts, (inset) Farnaz Kordbacheh.

engaged in refining techniques for growing cover crops, implementing conservation tillage, and using science-based nutrient management to reduce erosion and nutrient loss while increasing organic matter.

Acreage under irrigation has expanded modestly since 2002,[78] mostly in the northern part of the Midwest where coarse soils of lower water-holding capacity are more vulnerable to drying under increased temperature. No strategies currently are available for maintaining historical trends in commodity agriculture production to cope with increases in spring rainfall and summer heat waves projected for mid-century.[2,65]

Key Message 2

Forestry

Midwest forests provide numerous economic and ecological benefits, yet threats from a changing climate are interacting with existing stressors such as invasive species and pests to increase tree mortality and reduce forest productivity. Without adaptive actions, these interactions will result in the loss of economically and culturally important tree species such as paper birch and black ash and are expected to lead to the conversion of some forests to other forest types or even to non-forested ecosystems by the end of the century. Land managers are beginning to manage risk in forests by increasing diversity and selecting for tree species adapted to a range of projected conditions.

Forests are a defining characteristic of many landscapes within the Midwest, covering more than 91 million acres. From the oak–hickory forests of the Missouri Ozarks to the northern hardwood forests of the Upper Midwest, forest ecosystems sustain the people and communities within the region by providing numerous ecological, economic, and cultural benefits. The economic output of the Midwest forestry sector totals around $122 billion per year.[79,80,81,82,83,84,85,86] Forest-related recreation such as hunting, fishing, hiking, skiing, camping, wildlife watching, off-highway vehicles, and many other pursuits add to the region's economy. For example, forest-based recreationists spend approximately $2.5 billion (in 1996 dollars) within Wisconsin communities.[87] Forests are fundamental to cultural and spiritual practices within tribal communities, supporting plants and animals of central cultural importance and providing food and resources for making items such as baskets, canoes, and shelters.[88]

Climate change is anticipated to have a pervasive influence on forests within this region over the coming decades.[36,89,90,91,92,93,94] Tree growth rates and forest productivity have benefited from longer growing seasons and higher atmospheric carbon dioxide concentrations, but continued benefits are expected only if adequate moisture and nutrients are available to support enhanced growth rates.[95] As growing-season temperatures rise, reduced tree growth[96,97] or widespread tree mortality[98] is expected as the frequency of drought stress increases from drier air (as a result of increases in vapor pressure deficit [VPD]; Figure 21.3) and changing patterns of precipitation. Greater tree mortality from increased VPD likely will be particularly evident where competition for water is high in dense stands of trees[99,100] or where forests naturally transition to grasslands due to limited soil moisture.[101] Late-growing-season heat- and drought-related vegetation stress is projected to shift the composition and structure of forests in the region[102] by increasing mortality of younger trees, which are sensitive to drought.[19] Warming winters will reduce snowpack that acts to insulate soil from freezing temperatures, increasing frost damage to shallow tree roots[103] and reducing tree regeneration.[104] Additionally, increases in existing biological stressors of forests are expected as temperatures rise. Effects of insect pests and tree pathogens are anticipated to intensify as winters warm, increasing winter survival of pests and allowing expansion into new regions.[105,106] Changing climate conditions and atmospheric carbon dioxide concentrations will likely favor invasive plant species over native species, potentially decreasing tree regeneration.[107,108] Overall, the increasing stress on trees from rising temperatures, drought, and frost damage raises the susceptibility of individual trees to the negative impacts from invasive plants, insect pests, and disease agents (Ch. 6: Forests, Figure 6.1).[109,110,111]

Impacts from human activities such as logging, fire suppression, and agricultural expansion have lowered the diversity of the Midwest's forests from the pre-Euro-American settlement period. The forest types that occur within the region have been altered significantly relative to presettlement forests, with greater homogeneity in tree species composition across existing forest types.[112] Changes in modern forest types also include reduced structural complexity and less diverse mixes of tree species and tree ages.[113] Forests with reduced diversity are at an increased risk of negative effects from climate change, because the potential for tree species or age classes that are resistant to impacts from biological stressors and climate change is reduced.[93] Forests composed of trees of similar size and age or with lower tree diversity are at increased risk of widespread mortality[114,115] or declines in productivity.[116] In many midwestern forests, fire suppression has decreased the prevalence of

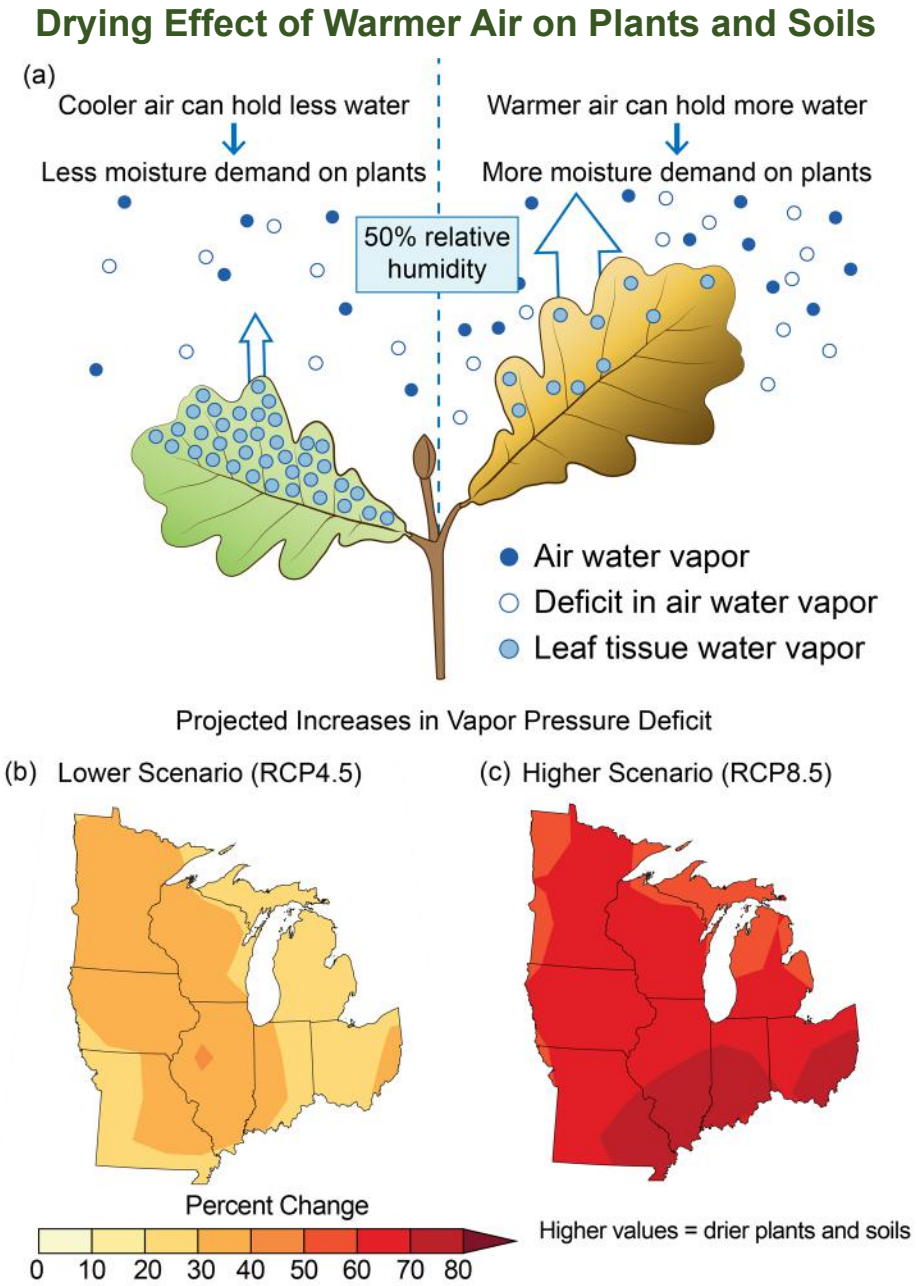


Figure 21.3: As air temperature increases in a warming climate, vapor pressure deficit (VPD) is projected to increase. VPD is the difference between how much moisture is in the air and the amount of moisture in the air at saturation (at 100% relative humidity). Increased VPD has a drying effect on plants and soils, as moisture transpires (from plants) and evaporates (from soil) into the air. (a) Cooler air can maintain less water as vapor, putting less demand for moisture on plants, while warmer air can maintain more water as vapor, putting more demand for moisture on plants. (b, c) The maps show the percent change in the moisture deficit of the air based on the projected maximum 5-day VPD by the late 21st century (2070–2099) compared to 1976–2005 for (b) lower and (c) higher scenarios (RCP4.5 and RCP8.5). Sources: U.S. Forest Service, NOAA NCEI, and CICS-NC.

the drought-tolerant tree species, such as oak, hickory, and pine, while increasing the abundance of species with higher moisture requirements, such as maples.[89,117] This results in greater risk of declines in forest health and productivity as the frequency of drought conditions increases.[118,119]

Changes in climate and other stressors are projected to result in changes in major forest types and changes in forest composition as tree species at the northern limits of their ranges decline and southern species experience increasingly suitable habitat.[120] However, the fragmentation of midwestern forests and

the flatness of the terrain raise the possibility that the ranges of particular tree species will not be able to shift to future suitable habitats within the Midwest.[121] For example, to reach areas 1.8°F (1°C) cooler, species in flat terrain must move up to 90 miles (150 km) north to reach cooler habitat, whereas species in mountainous terrain can shift higher in altitude over less latitudinal (north–south) distance.[122] These changes raise the possibility of future losses of economic and cultural benefits of forests due to conversion to different forest types or the change to non-forest ecosystems.[119,123,124] Projected shifts in forest composition in the central hardwood region (southern Missouri, Illinois, Indiana, and Ohio) by the end of the century under a higher scenario (RCP8.5) would result in substantial declines in wildlife habitat and reduce economic value of timber in the region by up to $788 billion (in 2015 dollars).[125]

Changing climate conditions increasingly cause both cultural and economic impacts within the Midwest, and it is very likely these impacts will worsen in the future. For example, many tree species on which tribes depend for their culture and livelihoods—such as paper birch, northern white cedar, and quaking aspen—are highly vulnerable due to temperature increases.[90,91,92,126] Populations of the emerald ash borer, a destructive invasive insect pest that attacks native ash trees, will increase due to warming winters in the region. Mortality of black ash trees, which are important for traditional basket-making for many tribes, is highly likely as winter temperatures continue to rise.[127]

Warming winters already have economic impacts on the forest industry, as well. Forest operations (for example, site access, tree harvesting, and product transport) in many northern regions are conducted on snowpack or frozen ground to protect the site from negative impacts such as soil disturbance and compaction,[128] but the timing of suitable conditions has become shorter and more variable. In the Upper Midwest, the duration of frozen ground conditions suitable for winter harvest has been shortened by 2 to 3 weeks in the past 70 years.[129] The contraction of winter snow cover and frozen ground conditions has increased seasonal restrictions on forest operations in these areas,[130] with resulting economic impacts to both forestry industry and woodland landowners through reduced timber values.[131]

Forestry professionals in the Midwest increasingly are considering the risks to forests from climate change[132] and are responding by incorporating climate adaptation into land management.[8] There are a growing number of examples of climate adaptation in forest management developed by more than 150 organizations that have participated in the Climate Change Response Framework, an approach to climate change adaptation led by the U.S. Forest Service.[133,134,135] Management actions intended to maintain healthy and productive forests in a changing climate include a diverse suite of actions[135] but largely focus on activities that enhance species and structural diversity of existing forest communities and on management approaches that aim to increase the prevalence of species that are better suited to future climatic conditions.[8] Forest management on tribal lands and ceded territory within the region increasingly integrates Scientific Ecological Knowledge of natural resource management with Traditional Ecological Knowledge, a highly localized, place-based system of knowledge learned and observed over many generations.[136] This integration can inform the co-creation of approaches to climate adaptation important for maintaining healthy, functioning forests that continue to provide cultural and spiritual benefits (see Case Study “Adaptation in Forestry”).

Case Study: Adaptation in Forestry

The Menominee Forest is well known as an exemplary forest; for generations, the Menominee Tribe has pioneered practices that have preserved nearly 220,000 acres with numerous species and varied habitats while maximizing the sustainable production of forest products. However, climate change—along with invasive species and insect pests and diseases—is creating new challenges for maintaining these diverse habitats and the sustainable supply of timber.

In response to tree mortality caused by oak wilt disease, an introduced exotic disease first identified in 1944 in Wisconsin, foresters at Menominee Tribal Enterprises (MTE) have integrated climate change adaptation into reforestation activities on severely disturbed areas created by the disease.[134] Using science guided by Traditional Ecological Knowledge of forest communities, forest openings created by oak wilt disease were replanted with a diverse array of tree and understory plant species that are expected to fare better under future climate conditions. Many of these species tolerate late-growing-season heat- and drought-related stress, while also providing important cultural benefits to the tribe such as food and medicine. The selection of locally collected plants and seeds used for restoring the oak wilt-affected openings combined scientific information on the future habitat of tree species with Indigenous knowledge of the forest communities necessary for guiding the development of diverse and healthy forests.

Figure 21.4: The photo shows Menominee Tribal Enterprises staff creating opportunity from adversity by replanting a forest opening caused by oak wilt disease with a diverse array of tree and understory plant species that are expected to fare better under future climate conditions. Photo credit: Kristen Schmitt.

> The grass, plant, and shrub species are put together to strengthen the immune system of the deep-rooted trees. We tried to emphasize the underground biotic community within these openings. A healthy underground community ensures a healthy aboveground community. The shrubs hold the key to a healthy change of species within the local plant communities.
>
> —MTE forester and tribal member

Key Message 3

Biodiversity and Ecosystems

The ecosystems of the Midwest support a diverse array of native species and provide people with essential services such as water purification, flood control, resource provision, crop pollination, and recreational opportunities. Species and ecosystems, including the important freshwater resources of the Great Lakes, are typically most at risk when climate stressors, like temperature increases, interact with land-use change, habitat loss, pollution, nutrient inputs, and nonnative invasive species. Restoration of natural systems, increases in the use of green infrastructure, and targeted conservation efforts, especially of wetland systems, can help protect people and nature from climate change impacts.

Species already are responding to environmental changes that have occurred over the last several decades,[17,18,19] and rapid climate change over the next century is expected to cause or further amplify stress in many species and ecological systems in the Midwest.[20,21,22] Land conversion and a wide range of other stressors have already greatly reduced biodiversity in many of the region's prairies, wetlands, forests, and freshwater systems. High rates of change in climate factors like air and water temperature and increasing drought risk likely will accelerate the rate of species declines and extinctions.[18,137] The Midwest region supports the world's largest freshwater ecosystem, the Great Lakes, which are at risk from rising temperatures, changes in seasonal stratification of lake temperatures, and increased summer evaporation rates, combined with stresses from pollution, nutrient inputs that promote harmful algal blooms, and invasive species (Box 21.1).

The loss of species and degradation of ecosystems have the potential to reduce or eliminate essential ecological services such as flood control, water purification, and crop pollination, thus reducing the potential for society to successfully adapt to ongoing changes.

Observations, ecological theory, experimental studies, and predictive models provide insights into how shifts in several climate factors (temperature, precipitation patterns, humidity, and moisture stress) may interact over the next several decades.[120,138,139] Vulnerability assessments for species and ecosystems quickly become complex, as species in the same ecosystem may have different climate sensitivities, and interactions with land-use change and other factors can strongly influence the level of impact (Ch. 5: Land Changes, KM 2; Ch. 17: Complex Systems, KM 1). Local expertise, input from multiple stakeholders, and tools like scenario planning can help improve assessment of vulnerability so that risks can be connected to management actions.[132,140] Changes observed in the Midwest include species range shifts (avoiding exposure to new climatic conditions by shifting location), changes in population size (indicating a change in viability in a given place), shifts in body size and growth rates, and changes in the timing of seasonal events (phenology). Since the Third National Climate Assessment,[27] the number of studies documenting these types of changes has continued to grow. For example, climate change appears to have contributed to the apparent local extinction of populations of the Federally Endangered Karner blue butterfly at sites in the southern end of its range in northern Indiana, despite active management and extensive habitat restoration efforts. While climate change cannot be singled out as the only cause, the populations disappeared following multiple years of warming conditions and a very early onset of spring in 2012.[139] New evidence of shifting ranges comes from

Wisconsin forests, where a set of 78 understory plant species sampled in the 1950s and again in the 2000s have demonstrated shifts in their abundance centroids (a measure of the distribution and local abundance of populations) of about 30 miles (49 km ± 29 km) over this 50-year period (Figure 21.5).[141] The dominant direction of this shift was to the northwest, which matches the direction of change in important climatic conditions associated with the distributions of these species. While this shift suggests the potential for successful adaptation to changing conditions, the rate of change for most species was much less than the amount of change in the climate metrics over the same time period, raising the concern that the climate is changing too fast for these species to keep up.[141] Similarly, a study of shifts in the timing of spring green-up, an indicator of when plant-feeding insects emerge, and the timing of migratory bird arrivals found that while both are shifting earlier in the Midwest, the arrival of birds is not advancing as quickly as the plants.[142] Risks to birds from this mismatch in phenology include the potential for birds to arrive after food availability has peaked or for later arrivals to be less able to compete for territories or mates. Land protection and management strategies that help maintain or increase phenological variation of plants within key migratory and breeding habitats like the Great Lakes coastlines may help increase the odds that birds can find the resources they need.[143]

The drivers of changes in species ranges or abundance can be complex and difficult to detect until key thresholds are crossed. For example, in the Midwest region, cool- and coldwater fishes in inland lakes are particularly susceptible to changes in climate because habitat with appropriate temperatures and oxygen concentrations is often limited during summer months. In lakes at the southern (warmer) end of their ranges, these fish experience a squeezing of available habitat during summer months as the water near the lake surface becomes too warm and the dissolved oxygen levels in deeper waters drop (Figure 21.6).[144,145,146] This "invisible" loss of habitat is driven by increases in water temperatures, longer duration of the stratified period (which delays the mixing of oxygen-rich water into the deeper waters), and declines in ice cover.[147,148,149,150] Recent research has identified fish kill events tied to temperature and oxygen stress from increased air temperatures, and modeling results forecast increased numbers of these events, likely leading to local extinction of cool- and coldwater fish species in some lakes and reduced geographic distribution across the Midwest.[151,152,153,154]

Climate Change Outpaces Plants' Ability to Shift Habitat Range

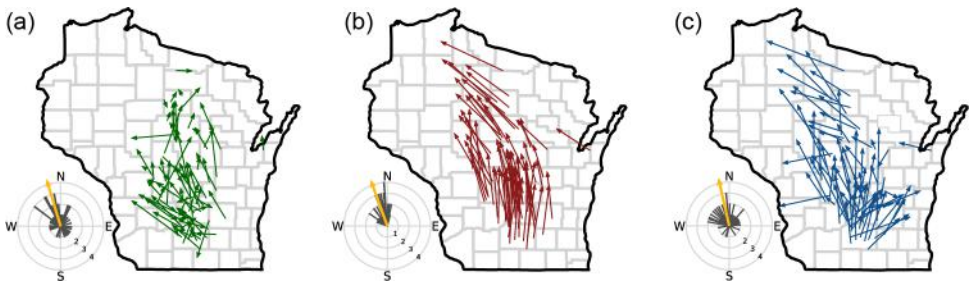


Figure 21.5: While midwestern species, such as understory plants in Wisconsin, are showing changes in range, they may not be shifting quickly enough to keep up with changes in climate. The panels here represent 78 plant species, showing (a) observed changes in the center of plant species abundances (centroids) from the 1950s to 2000s, (b) the direction and magnitude of changes in climate factors associated with those species, and (c) the lag, or difference, between where the species centroid is now located and where the change in climate factors suggests it should be located in order to keep pace with a changing climate. Source: adapted from Ash et al. 2017.[141] ©John Wiley & Sons, Ltd.

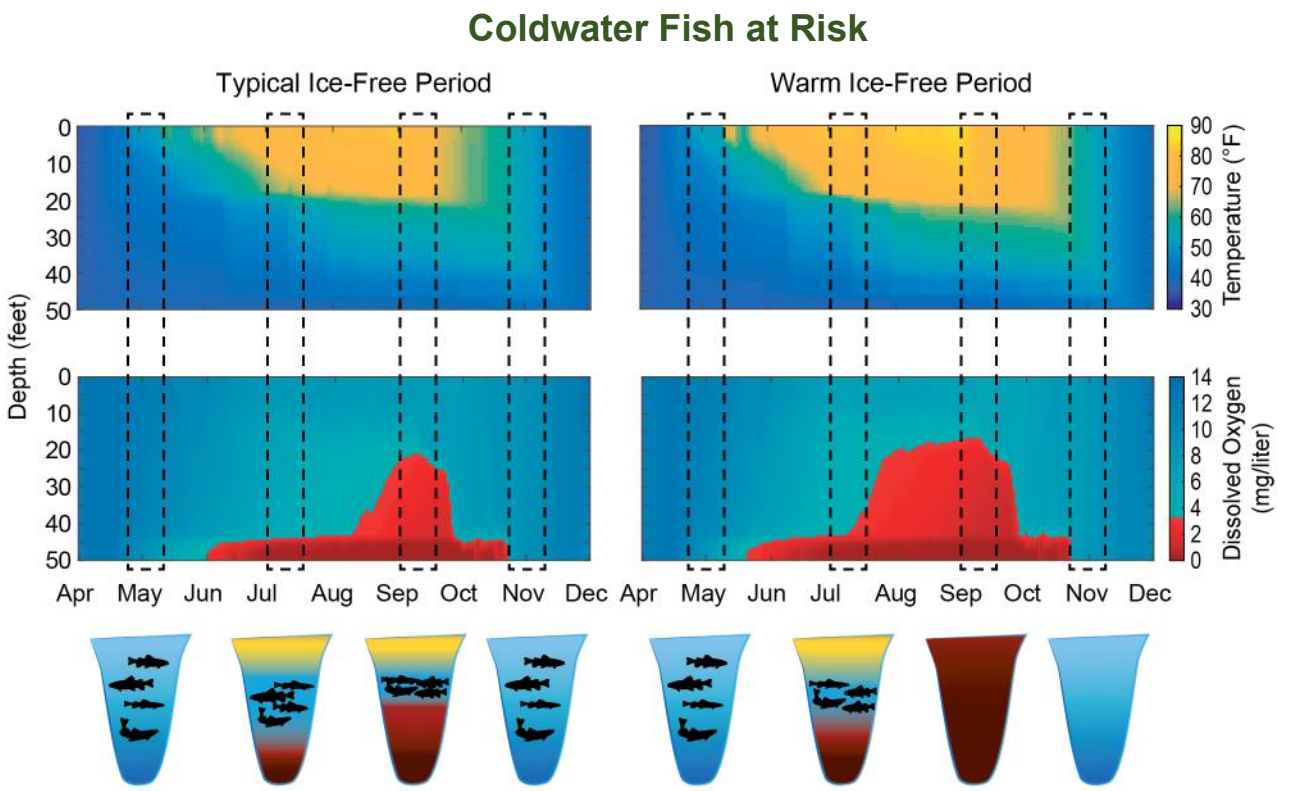


Figure 21.6: The graphic shows the oxythermal (oxygen and temperature) habitat of coldwater fish in midwestern inland lakes, illustrated by water depth under (left) a typical ice-free period and (right) a warm ice-free period (right). The top plots show water temperatures during the ice-free period, and the bottom plots show the dissolved oxygen concentrations. The schematics at the bottom illustrate the area of the lake that is ideal habitat for coldwater fish (in blue) and areas that represent water outside of the temperature or dissolved oxygen limit (in yellow and red, respectively). The left plots show how available habitat "squeezes" during a typical year, while the right plots illustrate a complete loss of suitable habitat during very warm years. Source: Madeline Magee, University of Wisconsin.

Taken individually, responses like range shifts, changes in local abundance, or changes in phenology may indicate that a species is successfully adapting to new conditions, or conversely may indicate a species is under stress. The extent to which responses indicate risk and the challenge of attributing changes to climate drivers when systems are exposed to many additional stressors are important sources of uncertainty that likely slow progress on climate change adaptation within the resource management sector.[155,156] Further, while evidence of species- and ecosystem-level responses to direct climate change impacts is increasing, many of the most immediate risks are even more challenging to track, because they relate to climate-driven enhancement of existing stressors, such as habitat loss and degradation, pollution, the spread of invasive species, and drainage and irrigation practices in agricultural landscapes.[138,157] As species are lost from midwestern ecosystems, there likely will be a net loss of biodiversity, as numerous additional stressors, especially widespread land conversion across the southern Midwest, limit opportunities for these gaps to be filled by species moving in from other regions (Ch. 7: Ecosystems, KM 1 and 2).[158,159]

While movement of species from the south-central United States could help sustain species-diverse ecosystems as some of the Midwest's current species move north, these range expansions can further stress current species. Many species and ecosystems in the Midwest, especially the Upper Midwest, are best suited to survive and compete for resources when winter conditions are harsh

and growing seasons are short. As winter warms and the growing season extends, species from the south-central United States, as well as species from outside the country that are more traditionally viewed as invasive species, are expected to be able to grow faster and take advantage of these changes, increasing the rate of loss of the region's native species.[160,161] For invasive insect pests, these impacts may be compounded as extended growing seasons allow time for additional generations to be produced in a single season;[162] the same mechanism can promote higher impacts from native insect pests, as well. Given that some native species will decline in the region, to maintain or increase species diversity, some managers are beginning to plan for and even promote some native plant species that are present in a region, but more common to the south, as conditions change. While these can be important strategies for maintaining diversity and ecosystem functions, especially in isolated habitats where inward migration is not likely, careful consideration of the source of plant stocks is important when seeking to avoid introducing new or more competitive genotypes.[163] Further, as some native species decline, managers will benefit from increased vigilance in keeping potential invasive species from outside of North America from gaining a foothold.

Declines in native pollinator species are another important concern in the Midwest, as both native and managed pollinator species (typically nonnative bee species) play vital roles in supporting food production and farmer livelihoods and are critical for supporting wild plant reproduction and the diversity of ecosystems.[164,165] Key threats to this diverse group of insects, mammals, and birds include habitat loss and degradation, pathogens, pesticide use, and invasive species.[164,165,166] Most native and agricultural crops that require a pollinator are pollinated by insects, and where information is available, declines in populations of pollinator insects in the Midwest have primarily been linked to the expansion of intensive agriculture.[167,168,169,170] In addition to habitat loss, climate change is likely to act as an added stressor for many species, through many different mechanisms.[164] Many insects may be limited by their ability to shift to new habitats as conditions change; for example, many bumble bee species are showing population declines at southern range edges but not expanding as quickly at northern range edges.[171] It is likely that pollinators that specialize on one or a few species for some aspect of their life history will be particularly vulnerable.[172] Within the Midwest, observed high rates of decline in the monarch butterfly,[167] which relies on milkweed species as a host plant, are the focus of a network of outreach and ambitious multi-partner conservation efforts that are helping raise awareness of pollinator declines and links between pollinators and habitat availability.[173] These efforts, boosted by research demonstrating that habitat restoration can help sustain pollinator populations,[174,175] provide examples of how to help support the adaptation of this critical group of species.

Perhaps more than in any other region of the United States, human land use has influenced the structure and function of natural systems of the Midwest. Widespread conversion of natural systems to agriculture has changed much of the region's water and energy balance (Ch. 5: Land Changes, KM 1). When vegetation has been removed or undergoes a major change, runoff and flooding both tend to increase.[24,176,177] As land has been cleared for agriculture and cities, it simultaneously has lost the capacity to store water due to the resulting conversion to pavement, compaction of soils, and widespread loss of wetlands. More than half of the region's wetlands have been drained (Ch. 22: N. Great Plains, Case Study "Wetlands and the Birds of the Prairie Pothole Region"); in states at the southern end of the region, fewer than

10%–15% of presettlement wetlands remained in the 1980s.[178] The growth of agriculture and loss of wetlands in the Midwest mean that changes to the timing, type (snow or rain), and amount of precipitation are acting on a system that is already highly altered in ways that tend to promote flooding.[24] Climate change modeling suggests that the southern half of the Midwest likely will see increases in saturated soils, which also indicates risks to agriculture and property from inundation and flooding;[179] recent work incorporating land-use change and population changes also suggests the number of people at risk from flooding will increase across much of the Midwest.[180] However, understanding these relationships also highlights important climate adaptation strategies. For example, restoring systems like wetlands and forested floodplains and implementing agricultural best management strategies that increase vegetative cover (such as cover crops and riparian buffers) can help reduce flooding risks and protect water quality (Figure 21.7).[23,24,25]

Wetland Restoration Projects Can Help Reduce Impacts

Figure 21.7: The Blausey Tract restoration project on the U.S. Fish and Wildlife Service's Ottawa National Wildlife Refuge (Ohio) restored 100 acres of former Lake Erie coastal wetlands that were previously in row crop production. In addition to providing habitat for wildlife and fish, these wetlands help reduce climate change impacts by storing water from high-water events and by filtering nutrients and sediments out of water pumped from an adjacent farm ditch. This work was carried out by two conservation groups, The Nature Conservancy and Ducks Unlimited, in partnership with the U.S. Fish and Wildlife Service, and was funded by The Great Lakes Restoration Initiative.[186,187] (top) Shown here is the Blausey Tract restoration site in early spring of 2011, prior to the restoration activities. (bottom) In the spring of 2013, just two years after the start of restoration, the site already was providing important habitat for wildlife and fish. Photo credits: (top) ©The Nature Conservancy, (bottom) Bill Stanley, ©The Nature Conservancy.

As the flooding risk example above illustrates, understanding both the history of change and how future climate patterns can drive additional changes is useful for identifying meaningful strategies for reducing risks to both people and biodiversity through strategically protecting and restoring ecosystems. Since the Third National Climate Assessment,[27] the recognition, promotion, and implementation of green or ecosystem-based climate change adaptation solutions have expanded. While the idea of using natural systems to reduce risks and provide benefits to society is not new, efforts to document and quantify benefits, costs, and costs savings (relative to hard, or "gray," infrastructure) of these types of approaches are increasing.[181] These approaches often help replace systems that have been lost, such as Great Lakes coastal wetlands, prairies, and vegetated floodplains along rivers and streams that slow water flows and act as sponges that keep floodwaters from people, property, and infrastructure (Figure 21.7),[182,183] or tree cover that increases shade and improves urban air quality.[181,184] The important role of nature-based solutions like reforestation for mitigating climate change is also increasingly being recognized and quantified.[185] From the perspective of protecting the biodiversity of the Midwest, adaptation and mitigation strategies that incorporate protection or restoration of natural systems can be a great win-win approach, because they often add habitat and restore ecological and hydrological functions that were reduced as a result of land conversion.

Box 21.1: Focus on the Great Lakes

The Great Lakes contain 20% of the world's surface freshwater, provide drinking water and livelihood to more than 35 million people,[188] and allow for important economic and cultural services such as shipping and recreation. The Great Lakes influence regional weather and climate conditions and impact climate variability and change across the region. The lakes influence daily weather by 1) moderating maximum and minimum temperatures of the region in all seasons, 2) increasing cloud cover and precipitation over and just downwind of the lakes during winter, and 3) decreasing summertime convective clouds and rainfall over the lakes.[189,190] In recent decades, the Great Lakes have exhibited notable changes that are impacting and will continue to impact people and the environment within the region.[191] In particular, lake surface temperatures are increasing,[11,12] lake ice cover is declining,[12,13,14] the seasonal stratification of temperatures in the lakes is occurring earlier in the year,[15] and summer evaporation rates are increasing.[13,16]

Along the Great Lakes, lake-effect snowfall has increased overall since the early 20th century. However, studies have shown that the increase has not been steady, and it generally peaked in the 1970s and early 1980s before decreasing.[193] As the warming in the Midwest continues, reductions in lake ice may increase the frequency of lake-effect snows until winters become so warm that snowfall events shift to rain.[194,195]

Lake-surface temperatures increased during the period 1985–2009 in most lakes worldwide, including the Great Lakes.[196] The most rapid increases in lake-surface temperature occur during the summer and can greatly exceed temperature trends of air at locations surrounding the lakes.[197] From 1973 to 2010, ice cover on the Great Lakes declined an average of 71%;[14] although ice cover was again high in the winters of 2014 and 2015,[192] a continued decrease in ice cover is expected in the future.[198,199]

Water levels in the Great Lakes fluctuate naturally, though levels more likely than not will decline with the changing climate.[200] A period of low water levels persisted from 1998 to early 2013. A single warm winter in

Box 21.1: Focus on the Great Lakes, *continued*

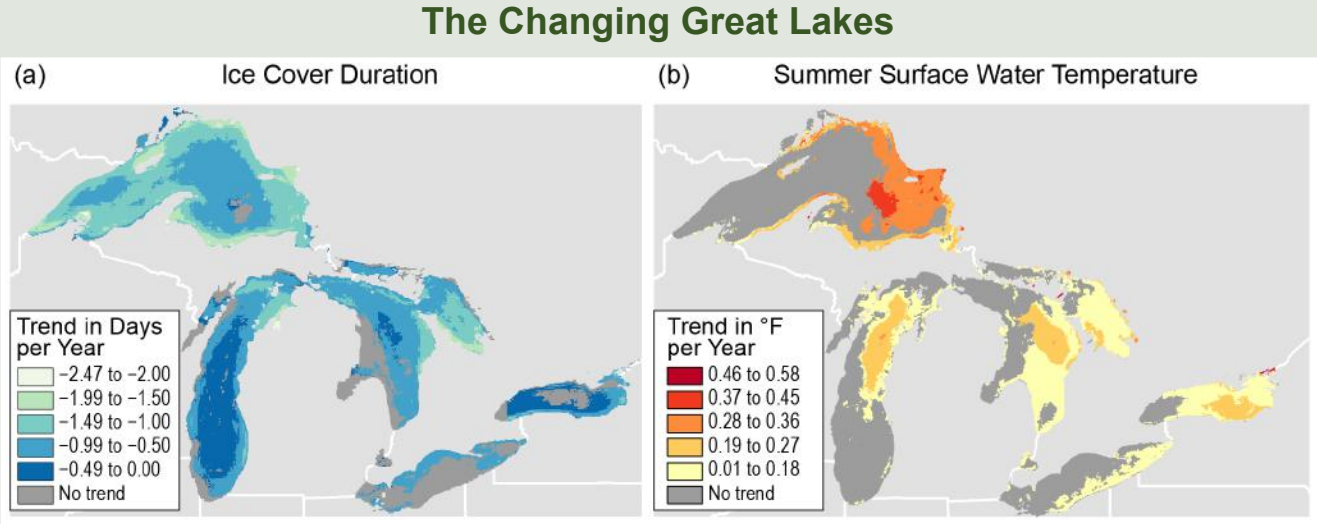


Figure 21.8: The duration of seasonal ice cover decreased in most areas of the Great Lakes between 1973 and 2013, while summer surface water temperature (SWT) increased in most areas between 1994 and 2013. (a) The map shows the rate of change in ice cover duration. The greatest rate of decrease in seasonal ice cover duration is seen near shorelines, with smaller rates occurring in the deeper central parts of Lakes Michigan and Ontario, which rarely have ice cover. (b) The map shows the rate of change in summer SWT. The greatest rates of increase in summer SWT occurred in deeper water, with smaller increases occurring near shorelines. Source: adapted from Mason et al. 2016.[192] Used with permission from Springer.

1997–1998 (corresponding to a major El Niño event) and ongoing increases in sunlight reaching the lake surface (due to reduced cloud cover) were likely strong contributors to these low water levels.[11] Following this period, water levels rose rapidly. Between January 2013 and December 2014, Lake Superior's water rose by about 2 feet (0.6 meters) and Lakes Michigan and Huron's by about 3.3 feet (1.0 meter).[201] Recent projections with updated methods of lake levels for the next several decades under 64 global model-based climate change simulations (from the Coupled Model Intercomparison Project Phase 5, or CMIP5 database, using the RCP4.5, RCP6.0, and RCP8.5 scenarios) on average show small drops in water levels over the 21st century (approximately 6 inches for Lakes Michigan and Huron and less for the other lakes), with a wide range of uncertainty.[200]

An important seasonal event for biological activity in the Great Lakes is the turnover of water, or destratification, which historically has occurred twice per year. Destratification occurs during the fall as the water temperature drops below a threshold of 39°F, the point at which freshwater attains its maximum density, and again during the spring when the water temperature rises above that threshold. The resultant mixing carries oxygen down from the lake surface and nutrients up from the lake bottom and into the water column. In a pattern that is similar to changes in duration of the growing season on land, the climate projections suggest that the overturn in spring that triggers the start of the aquatic "growing season" will happen earlier, and the fall overturn will happen later.[198,202] This trend toward a longer stratified season has been documented at locations in Lake Superior.[197,203] As the duration of the stratified period increases, the risk of impacts from low oxygen levels at depth and a lack of nutrient inputs at the surface increases, potentially leading to population declines of species in both zones. As warming trends continue, it is possible that a full overturning may not occur each year.[204] For example, lake surface temperatures failed to drop below the 39°F threshold during the winters of 2012 and 2017 in parts of southern Lake Michigan and Lake Ontario (see https://coastwatch.glerl.noaa.gov/glsea/glsea.html). When this lack of water mixing contributes to persistently low oxygen levels, the result may be reductions in the growth of phytoplankton (algae) and zooplankton (microscopic animals) that form the basis of aquatic food webs, potentially leading to cascading effects on the health and abundance of species across all levels of Great Lakes food webs.[202,205,206]

Box 21.1: Focus on the Great Lakes, *continued*

Ecological impacts of climate change in the Great Lakes occur in the context of multiple stressors, as these important ecosystems are under stress from pollution, nutrient and sediment inputs from agricultural systems, and invasive species (Ch. 17: Complex Systems, KM 1).[9,10] Human influence on habitats is another stressor. Examples include coastal wetland damage[207] and disturbance by human structures that change habitat conditions and water flow patterns.[208] Fish harvest and other management activities also have influences on populations.[209] Especially in Lake Erie, runoff from agricultural watersheds can carry large volumes of nutrients and sediments that can reduce water quality, potentially leading to hypoxia (inadequate oxygen supply),[210,211] an occurrence that is predicted to be more likely as the climate continues to change.[10] Increased water temperatures and nutrient inputs also contribute to algal blooms, including harmful cyanobacterial algae that are toxic to people, pets, and many native species.[212,213]

As with the inland lake fish described above (see Figure 21.6), climate change is expected to impact the species and fisheries of the Great Lakes.[214] However, the vast size and low temperatures in these lakes suggest that mortality events from temperature are a much lower risk. One key aspect of the influence of warming lakes on fish growth is the availability of suitable thermal habitat, as ectotherms, or cold-blooded species, can grow faster in warmer water due to temperature impacts on metabolic rates. Fish can behaviorally thermoregulate, meaning they can migrate to the portion of the water column that contains water of the particular species' preferred temperature.[215] Bottom-water temperatures in the deep parts of the lakes are expected to remain close to 39°F, while temperatures above the seasonal thermocline (the distinct temperature transition zone separating warmer surface waters from colder waters below) are expected to warm considerably.[202] This means that fish will be able to find habitats that favor higher growth rates for a longer period of time during the year. This same growth rate increase may occur for some species in smaller lakes, but the potential for exceeding critical thresholds is likely higher (Figure 21.6). If sufficient food is available, this will enhance the growth rates for economically important species like yellow perch and lake whitefish even though they are classed as cool-water and coldwater fishes, respectively.[216] It remains unclear, however, if a sufficient food supply will be available to sustain this increase in growth rates.

While some native fish may show enhanced growth, these same changes can influence the survival and growth of invasive species. Nonnative species such as alewife[217] and zebra and quagga mussels[218] have had dramatic impacts on the Great Lakes. Warmer conditions may lead to increases in invasion success and may increase the impact of invasive species that are already present. For example, sea lamprey are parasitic fish that are native to the Atlantic Ocean, and in the Great Lakes, they are the focus of several forms of control efforts.[219] Climate change has potential to reduce the effectiveness of these efforts. In the Lake Superior watershed, in years with longer growing seasons (defined as the number of days with water temperatures above 50°F), lamprey reach larger weights before spawning.[161] Larger body sizes suggest a greater impact on other fish species, because larger lamprey produce more eggs and require more food to survive.[161]

Coastal communities and several economic sectors, including shipping, transportation, and tourism, are vulnerable to the aforementioned climate impacts (Ch. 8: Coastal, KM 1). While the most recent research[200] underscores the great uncertainty in future lake levels, earlier research showed that scenarios of decreasing lake levels will increase shipping costs even if the shipping season is longer,[220] or that lower ice cover could increase the damage to coastal infrastructure caused by winter storms.[221,222] While several coastal communities have expressed willingness to integrate climate action into planning efforts, access to useful climate information and limited human and financial resources constrain municipal action. Producers and users of climate

Box 21.1: Focus on the Great Lakes, *continued*

information are working together to create customized climate information and resources, which increases trust and legitimacy, addressing this challenge (see Case Study "Great Lakes Climate Adaptation Network"). This has been demonstrated in projects, for instance, with marinas and harbors in Michigan, with ravine management in Illinois and Wisconsin, and with the Chicago Climate Action Plan in Illinois.[223,224,225,226] Although many communities in the region are taking steps to incorporate climate change and related impacts into policy and planning decisions, many more may benefit from using their existing stakeholder networks to engage with producers of climate information and build upon lessons learned from leaders in the region.[227]

Key Message 4

Human Health

Climate change is expected to worsen existing health conditions and introduce new health threats by increasing the frequency and intensity of poor air quality days, extreme high temperature events, and heavy rainfalls; extending pollen seasons; and modifying the distribution of disease-carrying pests and insects. By mid-century, the region is projected to experience substantial, yet avoidable, loss of life, worsened health conditions, and economic impacts estimated in the billions of dollars as a result of these changes. Improved basic health services and increased public health measures—including surveillance and monitoring—can prevent or reduce these impacts.

Climate change directly and indirectly impacts human health (Ch. 14: Human Health, KM 1). Midwestern populations are already experiencing adverse health impacts from climate change, and these impacts are expected to worsen in the future.[26,27] The risks are especially high for people who are less able to cope because characteristics like age, income, or social connectivity make them more vulnerable.[228]

Air Quality

Degraded air quality impacts people living in the Midwest. Increases in ground-level ozone and particulate matter are associated with the prevalence of various lung and cardiovascular diseases, which can lead to missed school days, hospitalization, and premature death (Ch. 13: Air Quality, KM 1).[26,28] Despite successful efforts to reduce particulate matter and ozone pollution, climate change could increase the frequency of meteorological conditions that lead to poor air quality.[26,229] In the absence of mitigation, ground-level ozone concentrations are projected to increase across most of the Midwest, resulting in an additional 200 to 550 premature deaths in the region per year by 2050.[28] These account for almost half of the total projected deaths due to the climate-related increase in ground-level ozone nationwide and may cost an estimated $4.7 billion (in 2015 dollars).[28]

Pollen production has been on the rise in the Midwest in recent years, with pollen seasons starting earlier and lasting longer (Ch. 13: Air Quality, KM 3).[28,230] People, particularly children, with asthma and other respiratory diseases are especially vulnerable to aeroallergens.[231] Aeroallergens can cause allergic rhinitis and exacerbate asthma and sinusitis.[231] Oak pollen may be responsible for an increase of 88 to 350 asthma-related emergency room visits by 2050 under the higher scenario (RCP8.5), with an estimated average annual cost ranging between $43,000 and $170,000 (in 2015 dollars).[28]

Projected Changes in Ozone-Related Premature Deaths

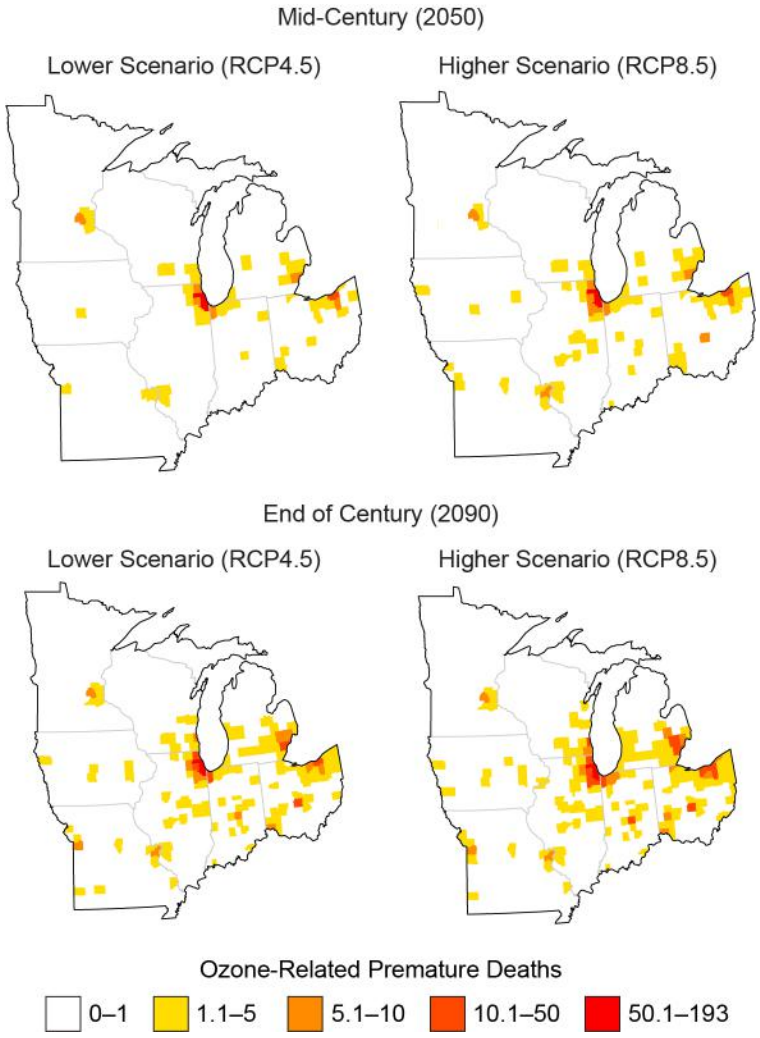


Figure 21.9: Maps show county-level estimates for the change in average annual ozone-related premature deaths over the summer months in 2050 (2045–2055) and 2090 (2085–2095) compared to 2000 (1995–2005) under the lower and higher scenarios (RCP4.5 and RCP8.5) in the Midwest. The results represent the average of five global climate models. Source: adapted from EPA 2017.[28]

Temperature

Increased daytime and nighttime temperatures are associated with heat-related diseases (for example, dehydration and heatstroke) and death in the Midwest.[26,232] Extreme heat in urban centers like Chicago, St. Louis, Cincinnati, Minneapolis/St. Paul, Milwaukee, and Detroit can cause dangerous living conditions.[26,232,233,234,235,236] High rates of heat-related illness also have been observed in rural populations,[235] where occupational exposure to heat and access to care is a concern. Exposure to high temperatures impacts workers' health, safety, and productivity.[29]

Future risk of heat-related disease could be significantly higher. As an example, Figure 21.10 shows the projected number of days over 100°F in Chicago over the 21st century using 32 models and two scenarios. Currently, days over 100°F in Chicago are rare. However, they could become increasingly more common in both the lower and higher scenarios (RCP4.5 and RCP8.5). The higher scenario (RCP8.5) yields a wider range and a higher number of days over 100°F than the lower scenario (RCP4.5), especially by 2070–2090. Near the upper end of the model results (95th percentile) at late-century, with the potential for almost 60 days per year

over 100°F, conditions could be more typical of present-day Las Vegas than Chicago. While the degree of uncertainty becomes larger further into the future, all model results show an increase in heat in the last two periods of the 21st century—changes that would pose a significant challenge to Chicago and other midwestern cities.

Compared to other regions where worsening heat is also expected to occur, the Midwest is projected to have the largest increase in extreme temperature-related premature deaths under the higher scenario (RCP8.5): by 2090, 2,000 additional premature deaths per year, compared to the base period of 1989–2000, are projected due to heat alone without adaptation efforts.[28] Northern midwestern communities and vulnerable populations (see Key Message 6) that historically have not experienced high temperatures may be at risk for heat-related disease and death. Risk of death from extremely cold temperatures will decrease under most climate projection scenarios.[28]

Unabated climate change will translate into costs among the workforce and in utility bills, potentially exacerbating existing health disparities among those most at risk. By 2050, increased temperatures under the higher scenario (RCP8.5) are estimated to cost around $10 billion (in 2015 dollars) due to premature deaths and lost work hours.[28] Increased electricity demand is estimated to amount to $1.2 billion by 2090 (in 2015 dollars).[28] For those who are chronically ill or reliant on electronic medical devices, the increased cost of electricity, which contributes to energy insecurity,[28] may introduce financial and health burdens.

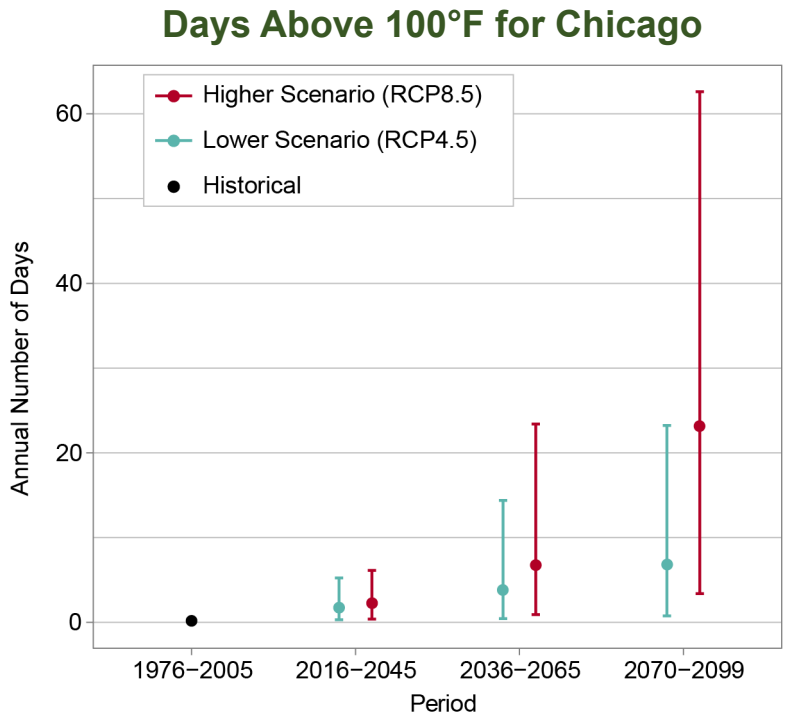


Figure 21.10: This graph shows the annual number of days above 100°F in Chicago for the historical period of 1976–2005 (black dot) and projected throughout the 21st century under lower (RCP4.5, teal) and higher (RCP8.5, red) scenarios. Increases at the higher end of these ranges would pose major heat-related health problems for people in Chicago. As shown by the black dot, the average number of days per year above 100°F for 1976–2005 was essentially zero. By the end of the century (2070–2099), the projected number of these very hot days ranges from 1 to 23 per year under the lower scenario and 3 to 63 per year under the higher scenario. For the three future periods, the teal and red dots represent the model-weighted average for each scenario, while the vertical lines represent the range of values (5th to 95th percentile). Both scenarios show an increasing number of days over 100°F with time but increasing at a faster rate under the higher scenario. Sources: NOAA NCEI and CICS-NC.

Precipitation

An increase in localized extreme precipitation and storm events can lead to an increase in flooding.[27] River flooding in large rivers like the Mississippi, Ohio, and Missouri Rivers and their tributaries can flood surface streets and low-lying areas, resulting in drinking water contamination, evacuations, damage to buildings, injury, and death.[26] Flooded buildings can experience mold growth that can trigger asthma attacks and allergies during cleanup efforts.[237] Mental stress following flooding events can cause substantial health impacts, including sleeplessness, anxiety, depression, and post-traumatic stress disorder.[238] Similarly, drought has been identified as a slow-moving stressor that contributes to acute and chronic mental health impacts such as anxiety and depression.[239]

Precipitation events can transport pathogens that cause gastrointestinal illnesses, putting populations who rely on untreated groundwater (such as wells) at an increased risk of disease,[240] particularly following large rainfall events.[241] Many midwestern communities use wells as their drinking water sources. Adaptive measures, such as water treatment installations, may substantially reduce the risk of gastrointestinal illness, in spite of climate change.[240]

Habitat Conditions

Climate-related changes in habitats (see Key Message 3) for disease-carrying insects like the mosquito found in the Midwest (*Culex pipiens* and *Culex tarsalis*) that transmits West Nile virus (WNV) and the blacklegged, or deer, tick (*Ixodes scapularis*) that transmits Lyme disease have been associated with higher rates of infection.[242,243] Northern expansion of the *Culex* species in the Midwest is expected to result in upwards of 450 additional WNV cases above the 1995 baseline by 2090 absent greenhouse gas mitigation.[28]

Harmful algal blooms (Box 21.1), such as one that occurred in August 2014 in Lake Erie, can introduce cyanobacteria into drinking and recreational water sources, resulting in restrictions on access and use.[28] Contact with and consumption of water contaminated with cyanobacteria have been associated with skin and eye irritation, respiratory illness, gastrointestinal illness, and liver and kidney damage.[26] The occurrence of conditions that encourage cyanobacteria growth, such as higher water temperatures, increased runoff, and nutrient-rich habitats, are projected to increase in the Midwest.[28]

Challenges and Opportunities

Climate-sensitive health impacts are complex and dynamic. Coordination across public health, emergency preparedness, planning, and communication agencies can maximize outreach to the most at-risk populations while directing activities to reduce health disparities and impacts.[244] Public health agencies in the Midwest have developed interdisciplinary communities of practice around climate and health adaptation efforts, effectively enhancing the resilience of the region's public health systems.[244,245,246,247,248] Activities around increased surveillance of climate-sensitive exposures and disease are gaining momentum and interest among practitioners and researchers.[249,250]

Actions tied to reducing contributions to global climate change can result in direct co-benefits related to health and other outcomes (such as economic development).[251] Reducing emissions related to energy production and transportation may involve changes to fuel sources, vehicle technology, land use, and infrastructure.[251] Active transportation, such as biking and walking, has been found to significantly decrease disease burden.[252,253,254] A study of the 11 largest midwestern metropolitan areas estimated a health benefit of nearly 700 fewer deaths per year by swapping half of short trips

from car to bike.[255] As Midwest Rust Belt metropolitan areas revitalize and reinvest, there are opportunities to prioritize active living to maximally reduce climate change drivers and improve health.

Key Message 5

Transportation and Infrastructure

Storm water management systems, transportation networks, and other critical infrastructure are already experiencing impacts from changing precipitation patterns and elevated flood risks. Green infrastructure is reducing some of the negative impacts by using plants and open space to absorb storm water. The annual cost of adapting urban storm water systems to more frequent and severe storms is projected to exceed $500 million for the Midwest by the end of the century.

Climate change poses several challenges to transportation and storm water systems in the Midwest. Annual precipitation in the Midwest has increased by 5% to 15% from the first half of the last century (1901–1960) compared to present day (1986–2015).[193] Winter and spring precipitation are important to flood risk in the Midwest and are projected to increase by up to 30% by the end of this century. Heavy precipitation events in the Midwest have increased in frequency and intensity since 1901 and are projected to increase through this century.[193]

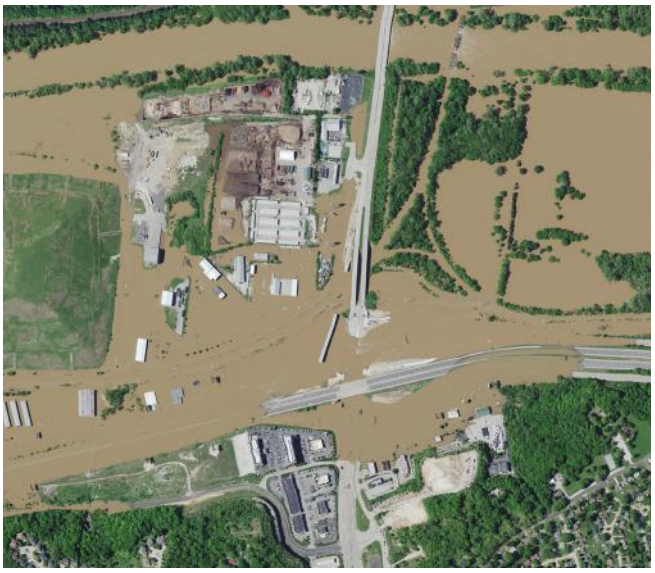
There has been an increase in extreme precipitation events that overwhelm storm water sewage systems, disrupt transportation networks, and cause damage to infrastructure and property. Runoff from extreme precipitation events can exceed the capacity of storm water systems, resulting in property damage, including basement backups (Ch. 11: Urban, KM 2).[37,256] In addition, in metropolitan areas with older sewer systems that combine sanitary sewage with storm water, extreme rain can result in the release of raw sewage into rivers and streams, posing both health and ecological risks.[257] These releases, known as combined sewer overflows (CSO), pose challenges to major sources of drinking water including the Mississippi River[258] and the Great Lakes.[259,260] On the Great Lakes, increases in CSO frequency and volume are projected under mid-high and higher scenarios (RCP6.0 and RCP8.5).[261] The U.S. Environmental Protection Agency (EPA) estimates that the cost of adapting urban storm water systems to handle more intense and frequent storms in the Midwest could exceed $480 million per year (in 2015 dollars) by the end of the century under either the lower or higher scenario (RCP4.5 or RCP8.5).[28] Extreme precipitation events also affect transportation systems (Ch. 12: Transportation, KM 1). Heavy rainstorms can result in the temporary closure of roadways. In addition, faster streamflow caused by extreme precipitation can erode the bases of bridges, a condition known as scour. A study of six Iowa bridges deemed to be critical infrastructure found that under all emissions scenarios (in the Coupled Model Intercomparison Project Phase 3), each location was projected to have increased vulnerability from more frequent episodes of overtopping and potential scour.[55] The EPA estimates that the annual cost of maintaining current levels of service on midwestern bridges in the face of increased scour damage from climate change could reach approximately $400 million in the year 2050 under either the lower or higher scenario (RCP4.5 or RCP8.5).[28]

In addition to its impacts on infrastructure, heavy precipitation also affects the operation of roadways by reducing safety and capacity while increasing travel times (Ch. 12: Transportation, KM 1). Projected increases in the number of extreme precipitation events have

been linked to an increased risk of traffic crashes.[262] Intelligent Transportation Systems (ITS) use sensors and cameras to monitor road conditions. This allows for rapid deployment of emergency response vehicles and use of electronic signage to reroute traffic. Such systems allow transportation agencies to minimize the adverse impacts associated with extreme weather.[263]

Flooding on major rivers also poses a challenge to Midwest communities. Major river floods differ from flash floods on smaller streams in that they affect a larger area and require longer periods of heavy precipitation to create flood conditions. The Nation's two largest rivers, the Mississippi and the Missouri, flow through the Midwest. River floods can cause loss of life, as well as significant property damage. River floods have caused the closure of interstate highways in the Midwest and temporary inundation of secondary roads. During floods in May 2017, more than 400 state roads in Missouri were closed due to flooding, including several stretches of Interstate 44 (Figure 21.11).[264] High water also disrupts barge traffic on the Mississippi River.[265,266,267,268,269,270] Billion-dollar floods in the Midwest have occurred three times in the last quarter-century.[271] Climate projections suggest an increased risk of inland flooding under either the lower or higher scenario (RCP4.5 or RCP8.5). Average annual damages from heightened flooding risk in the Midwest are projected to be in excess of $500 million (in 2015 dollars) by 2050.[28]

Changes in temperature also can pose challenges to infrastructure. Extreme heat creates material stress on road pavements, bridge expansion joints, and railroad tracks. Milder winter temperatures, however, may be expected to partially offset these damages by reducing the amount of rutting caused by the freeze–thaw cycle. Even taking into account the benefits of milder winters for paved surfaces, the EPA estimates that higher temperatures associated with unmitigated climate change would result in approximately $6 billion annually in added road maintenance costs and over $1 billion in impacts to rail transportation by 2090 (in 2015 dollars).[28]



River Flooding in the Midwest

Figure 21.11: This composite image shows portions of Interstate 44 near St. Louis that were closed by Meramec River flooding in both 2015 and 2017. The flooding shown here occurred in May 2017. Image credit: Surdex Corporation.

Green infrastructure—the use of plants and open space to manage storm water—is helping communities in the Midwest become more resilient to challenges associated with heavy precipitation. At the site or neighborhood level, rain gardens and other planted landscape elements collect and filter rainwater in the soil, slowing runoff into sewer systems. Permeable pavements on parking lots allow water to be stored in the soil. Trees planted next to streets also provide important storm water management benefits. Larger-scale projects include preservation of wetlands. In addition to their storm water management benefits, some types of green infrastructure, such as urban trees and green roofs, contribute to climate change mitigation by acting as carbon sinks.[272,273,274]

There are many examples of green infrastructure projects in the Midwest, though not all explicitly identify climate change as a rationale. The examples below enhance resilience to the heavy rains that are projected to become more frequent.

- The Cermak/Blue Island Sustainable Streetscape Project in the Pilsen neighborhood of Chicago uses bioswales, rain gardens, and permeable pavements to reduce up to 80% of storm water runoff. It also uses street trees and other vegetation to reduce the urban heat island effect while also providing an attractive public space.[275]

- The Metropolitan Sewer District in St. Louis has embarked upon a $100 million rainscaping project designed to divert storm water runoff in the northern portion of the City of St. Louis and adjacent north St. Louis County.[276]

- The City of Minneapolis uses street trees to reduce storm water runoff through enhanced evaporation and infiltration of water into the soil.[277] The City of Cleveland also prioritizes tree planting as an adaptation strategy, with an emphasis on increasing the tree canopy in low-income neighborhoods. In addition to its storm water management benefits, urban forestry also reduces the urban heat island effect and acts as a carbon sink.[278]

At the scale of a metropolitan region, preservation and restoration of streams, floodplains, and watersheds are enhancing biodiversity while also reducing storm water runoff.

- *Open Space Preservation*: Many communities in the Midwest are recognizing that preservation of open space, particularly in floodplains, is a cost-effective method for managing storm water. Ducks Unlimited, a non-profit organization, has purchased conservation easements that restrict future development on nearly 10,000 acres of floodplain around the confluence of the Mississippi and Missouri Rivers. In the Milwaukee area, the Ozaukee Washington Land Trust has preserved more than 6,000 acres of forests, wetlands, and open space through acquisitions and the purchase of conservation easements, preserving lands important for absorbing rainwater and filtering toxins from sediment.[279,280]

- *Stream Restoration:* Several midwestern communities are turning to dechannelization (the removal of concrete linings placed in waterways) and daylighting (bringing back to the surface streams that had been previously buried in pipes) as methods of storm water management. The Milwaukee Metropolitan Sewerage District is currently undertaking a dechannelization of the Kinnickinnic River. According to the District, the concrete lining of the waterway actually makes the waterway more dangerous during heavy rain. Flooding motivated the City of Kalamazoo to daylight a 1,500-foot section of Arcadia Creek in the downtown district.[281,282]

- *Ravine Restoration*: Lake Michigan's western shore in Wisconsin and northern Illinois holds more than 50 small watersheds, known locally as ravines. Storm water runoff subjects these ravines to serious erosion, which threatens property and infrastructure. The Great Lakes Alliance has produced guides to reduce erosion through best management practices, including stream buffers, use of native plants for stabilization, and reducing the steepness or gradient of the stream bank.[223]

Key Message 6

Community Vulnerability and Adaptation

At-risk communities in the Midwest are becoming more vulnerable to climate change impacts such as flooding, drought, and increases in urban heat islands. Tribal nations are especially vulnerable because of their reliance on threatened natural resources for their cultural, subsistence, and economic needs. Integrating climate adaptation into planning processes offers an opportunity to better manage climate risks now. Developing knowledge for decision-making in cooperation with vulnerable communities and tribal nations will help to build adaptive capacity and increase resilience.

Vulnerability and Adaptation

In the Midwest, negative impacts related to climate change are projected to affect human systems, including cities, rural and coastal communities, and tribes.[28,283,284] Higher temperatures, increasing variation in precipitation patterns, and changes in lake levels are likely to increase the vulnerability of these systems to extreme events (including flooding, drought, heat waves, and more intense urban heat island effects), compounding already existing stressors such as economic downturns, shrinking cities, and deteriorating infrastructure.[285] Extreme heat such as that experienced in July 2011 (with temperatures reaching over 100°F in the majority of the Midwest) is expected to intensify,[286] and urban heat islands may cause hardships to those most vulnerable, such as the old and infirm and those without resources to control their microclimate (for example, through the use of air conditioning).[287] Under the higher scenario (RCP8.5), extreme heat is projected to result in losses in labor and associated losses in economic revenue up to $9.8 billion per year in 2050 and rising to $33 billion per year in 2090 (in 2015 dollars).[28] Expanding the use of green infrastructure and locating it properly may mitigate the negative impact of heat islands in urban settings (see Key Messages 4 and 5) (see also Ch. 11: Urban, KM 4).

To mitigate or better respond to these impacts, scholars and practitioners highlight the need to engage in risk-based approaches that not only focus on assessing vulnerabilities but also include effective planning and implementation of adaptation options (Ch. 28: Adaptation, KM 3).[32] These place-based approaches actively rely on participatory methodologies to evaluate and manage risk and to monitor and evaluate adaptation actions.[32] However, documented implementation of climate change planning and action in Midwest cities and rural communities remains low. For example, in 2015, only four counties and cities in the region—Marquette and Grand Rapids in Michigan and Dane County and Milwaukee in Wisconsin—had created formal climate adaptation plans, none of which have been implemented.[288] Moreover, a recent study of 371 cities in the Great Lakes region found that only 36 of them could identify a climate entrepreneur, that is, a public official clearly associated with pushing for climate action.[285] Attempts to assess vulnerabilities, especially for poor urban communities, face persisting environmental and social justice barriers, such as lack of participation and historical disenfranchisement,[289] despite evidence that these communities are going to be disproportionately affected by climate impacts.[290] Additionally, in-depth interviews with local decision-makers on water management across scales have suggested that a lack of political and financial support at the state and federal levels is a barrier to adaptation action in cities and counties.[291] While initiatives are underway in the Midwest to mainstream

adaptation action—that is, embed and integrate climate adaptation action in what cities already do (see Case Study "Great Lakes Climate Adaptation Network") (see also Ch. 28: Adaptation, KM 5)—there are few examples in the published literature that document failure or success (but see Kalafatis et al. 2015, Vogel et al. 2016[292,293]).

Case Study: Great Lakes Climate Adaptation Network

The Great Lakes Climate Adaptation Network (GLCAN) is a regional, member-driven peer network of local government staff who work together to identify and act on the unique climate adaptation challenges of the Great Lakes region. GLCAN formed in 2015 as a regional network of the Urban Sustainability Directors' Network (USDN) to unite Great Lakes cities with universities in the region. It has been cooperating actively with a regional climate organization, the Great Lakes Integrated Sciences and Assessments (GLISA), a NOAA-supported program housed at the University of Michigan and Michigan State University, to create climate information in support of decision-making in member cities. In this example of sustained engagement, GLCAN and GLISA work as a boundary chain that moves climate information from producers at the Universities to users in the cities, as well as across cities. This minimizes transaction costs, in terms of human and financial resources, while building trust and legitimacy.[292,294] In one example of this partnership, with funding from USDN, GLCAN and GLISA worked with the Huron River Watershed Council and five Great Lakes cities (Ann Arbor, Dearborn, Evanston, Indianapolis, and Cleveland) to develop a universal vulnerability assessment template that mainstreams the adaptation planning process and results in the integration of climate-smart and equity-focused information into all types of city planning.[295] The template is publicly available;[296] its purpose is to reduce municipal workloads and save limited resources by mainstreaming existing, disparate planning domains (such as natural hazards, infrastructure, and climate action), regardless of city size or location. Based on this work, USDN funded a follow-up project for GLISA to work with additional Great Lakes and Mid-Atlantic cities and a nonprofit research group (Headwaters Economics) to develop a socioeconomic mapping tool for climate risk planning.

Linked Boundary Chain Model

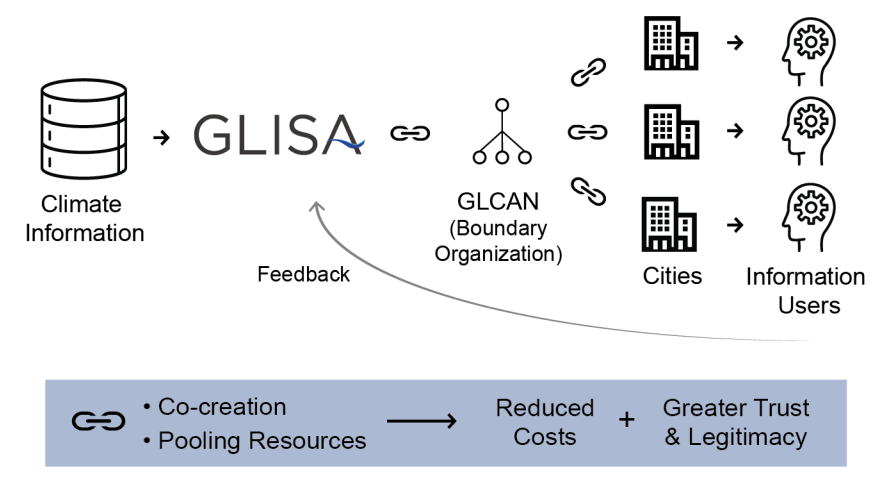


Figure 21.12: Shown here is a configuration of the boundary chain employed in the Great Lakes Climate Adaptation Network (GLCAN) Case Study. The information is tailored and moves through different boundary organizations (links in the chain) to connect science to users. By co-creating information and pooling resources throughout the chain, trust and legitimacy are built and cost is decreased. Source: adapted from Lemos et al. 2014.[294] ©American Meteorological Society.

In addition, work on estimating the cost of adaptation nationally and in the Midwest remains limited, though the EPA has estimated that the Midwest is among the regions with the largest expected damages to infrastructure, including the highest estimated damages to roads, rising from $3.3 billion per year in 2050 to $6 billion per year in 2090 (in 2015 dollars) under a higher scenario (RCP8.5), and highest number of vulnerable bridges (Key Message 5).[28] Additionally, economic models that value climate amenities—for example, offering residents the benefits of warmer winters or cooler summers—indicate that while the Midwest is among the regions with the largest predicted amenity loss, certain cities (such as Minneapolis and Minnesota) and subregions (such as upper Michigan) will be among the few places where the value of warmer winters outweighs the cost of hotter summers.[297,298] Limited evidence indicates that household consideration of climate amenities may contribute to reversing long-standing trends in out-migration from the Midwest[298] and that changes in national migration patterns will contribute to population growth in the region.[28] More research is needed to understand how cities in the Midwest might be affected by long-term migration to the region.[31]

Collaboratively Developing Knowledge and Building Adaptive Capacity

Interactions among producers of climate information (for example, universities and research institutes), end users (such as city planners, watershed managers, and natural resource managers), and intermediaries (for example, information brokers and organizations) play a critical role in increasing the integration and use of climate knowledge for adaptation.[299] In the Midwest, organizations such as the Great Lakes Integrated Sciences and Assessments (GLISA; glisa.umich.edu) and the Wisconsin Initiative on Climate Impacts (wicci.wisc.edu), and research projects such as Useful to Usable (U2U), have created mechanisms and tools, such as climate scenarios, decision support tools, and climate data, that promote the joint development of usable climate information across different types of stakeholders, including city officials, water managers, farmers, and tribal officials.[224,294,300] For example, working closely with corn farmers and climate information intermediaries, including extension agents and crop consultants, in Iowa, Nebraska, Michigan, and Indiana, an interdisciplinary team of climate scientists, agronomists, computer scientists, and social scientists have not only created a suite of decision support tools (see Key Message 1) but also significantly advanced understanding of corn farmers' perceptions of climate change,[301] willingness to adapt,[302] and opportunities for and limitations of the use of climate information in the agricultural sector.[294,303] Strategies being implemented as a result of these collaborations, including the use of green infrastructure and water conservation efforts, are proving effective at reducing sensitivity to the impacts of climate change in the Midwest.[304,305,306] In addition, binational partnerships between the United States and Canada, in support of the Great Lakes Water Quality Agreement, synthesized annual climate trends and impacts for a general audience in a pilot product for 2017 to provide a timely and succinct summary in an easy-to-understand format (Ch. 16: International, KM 4).[307] However, these organizations face challenges including the high costs in interacting with users, contextualizing and customizing climate information, and building trust.[308] The development of new forms of sustained engagement likely would increase the use of climate information in the region.

Tribal Adaptation

Tribes and Indigenous communities in the Midwest have been among the first to feel the effects of climate change as it impacts their culture, sovereignty, health, economies, and ways of life.[39] The Midwest contains ceded territory—large swaths of land in Minnesota, Wisconsin, and Michigan in which Ojibwe tribes reserved hunting, fishing, and gathering

rights in treaties with the United States government.[88] Climate change presents challenges to the Ojibwe tribes in co-managing these resources with other land managers; as the climate changes, various species utilized by tribes are declining and may shift entirely outside of treaty boundaries and reserved lands.[127,309,310] In certain tribal cultures, all beings (species) are important; climate adaptation efforts that favor certain beings at the detriment of others can be problematic. Adaptation to climate change might also mean giving up on something deeply embedded in tribal culture for which no substitute exists.[31] A family sugarbush (a forest stand used for maple syrup), for example, cannot be replaced culturally, spiritually, or economically if the sugar maple range were to shift outside of treaty or reservation boundaries. As the effects of climate change become more pronounced, further research can shed light on how tribal nations are being affected.

Projected changes in climate, particularly increases in extreme precipitation events, will have pronounced impacts on tribal culture and tribal people in the Midwest.[283] Reservations often are located in isolated rural communities, meaning emergency response to flooding presents challenges in getting help to tribal citizens. Additionally, in areas of the Midwest, infestations of the invasive emerald ash borer already are devastating ash tree populations and corresponding Indigenous cultural and economic traditions.[127]

Across the United States, a number of tribal nations are developing adaptation plans, including in the Midwest (Ch. 15: Tribes, KM 3).[283] These plans bring together climate data and projections with Traditional Ecological Knowledge [311,312] of tribal members. Within Indigenous oral history lies a complex and rich documentation of local ecosystems—not found in books—that can be used to understand and document the changes that are occurring.[313] Climate change effects are not typically immediate or dramatic because they occur over a relatively long period of time, but tribal elders and harvesters have been noticing changes, such as declining numbers of waabooz (snowshoe hare), many of which Scientific Ecological Knowledge has been slower to document. The Traditional Ecological Knowledge of elders and harvesters who have lived and subsisted in a particular ecosystem can provide a valuable and nuanced understanding of ecological conditions on a smaller, more localized scale. Integrating this Traditional Ecological Knowledge with Scientific Ecological Knowledge in climate change initiatives provides a more complete understanding of climate change impacts.[136] Community input to tribal adaptation plans ensures that Traditional Ecological Knowledge can be used to produce adaptation strategies trusted by community members.[314]

Acknowledgments

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Traceable Accounts

Process Description

The chapter lead authors were identified in October 2016, and the author team was recruited in October and November 2016. Authors were selected for their interest and expertise in areas critical to the Midwest with an eye on diversity in expertise, level of experience, and gender. The writing team engaged in conference calls starting in December 2016, and calls continued on a regular basis to discuss technical and logistical issues related to the chapter. The Midwest chapter hosted an engagement workshop on March 1, 2017, with the hub in Chicago and satellite meetings in Iowa, Indiana, Michigan, and Wisconsin. The authors also considered other outreach with stakeholders, inputs provided in the public call for technical material, and incorporated the available recent scientific literature to write the chapter. Additional technical authors were added as needed to fill in the gaps in knowledge.

Discussion amongst the team members, along with reference to the Third National Climate Assessment and conversations with stakeholders, led to the development of six Key Messages based on key economic activities, ecology, human health, and the vulnerability of communities. In addition, care was taken to consider the concerns of tribal nations in the northern states of the Midwest. The Great Lakes were singled out as a special case study based on the feedback of the engagement workshop and the interests of other regional and sector chapters.

Note on regional modeling uncertainties

Interaction between the lakes and the atmosphere in the Great Lakes region (e.g., through ice cover, evaporation rates, moisture transport, and modified pressure gradients) is crucial to simulating the region's future climate (i.e., changes in lake levels or regional precipitation patterns).[315,316] Globally recognized modeling efforts (i.e., the Coupled Model Intercomparison Project, or CMIP) do not include a realistic representation of the Great Lakes, simulating the influence of the lakes poorly or not at all.[192,198,317,318,319] Ongoing work to provide evaluation, analysis, and guidance for the Great Lakes region includes comparing this regional model data to commonly used global climate model data (CMIP) that are the basis of many products practitioners currently use (i.e., NCA, IPCC, NOAA State Climate Summaries). To address these challenges, a community of regional modeling experts are working to configure and utilize more sophisticated climate models that more accurately represent the Great Lakes' lake–land–atmosphere system to enhance the understanding of uncertainty to inform better regional decision-making capacity (see http://glisa.umich.edu/projects/great-lakes-ensemble for more information).

Key Message 1

Agriculture

The Midwest is a major producer of a wide range of food and animal feed for national consumption and international trade. Increases in warm-season absolute humidity and precipitation have eroded soils, created favorable conditions for pests and pathogens, and degraded the quality of stored grain (*very likely, very high confidence*). Projected changes in precipitation, coupled with rising extreme temperatures before mid-century, will reduce Midwest agricultural productivity to levels of the 1980s without major technological advances (*likely, medium confidence*).

Description of evidence base

Humidity is increasing. Feng et al. (2016)[3] show plots of trends in surface and 850 hPa specific humidity of 0.4 and 0.2 g/kg/decade, respectively, from 1979–2014 for the April–May–June period across the Midwest. These represent increases of approximately 5% and 3% per decade, respectively. Automated Surface Observing Stations in Iowa[320] having dew point records of this length and season show dew point temperature increases of about 1°F per decade. Brown and DeGaetano (2013)[49] show increasing dew points in all seasons throughout the Midwest. Observed changes in annual average maximum temperature for the Midwest over the 20th century (Vose et al. 2017,[54] Table 6.1) have been less than 1°F. However, future projected changes in annual average temperature (Vose et al. 2017,[54] Table 6.4), as well as in both warmest day of the year and warmest 5-day 1-in-10 year events (Vose et al. 2017,[54] Table 6.5), are higher for the Midwest than in any other region of the United States.

Garbrecht et al. (2007)[321] state that precipitation changes are sufficient to require U.S. policy changes for agricultural lands. The Soil Erosion Site (http://soilerosion.net/water_erosion.html) describes the soil erosion process and provides links to soil erosion models.[322] Nearing et al. (2004)[44] report that global climate models project increases in erosivity (the ability or power of rain to cause soil loss) across the northern states of the United States over the 21st century.

Spoilage in stored grain is caused by mold growth and insect activity, which are related to the moisture content and temperature of the stored grain.[323] The ability of fungi to produce mycotoxins, including aflatoxin and fumonisins, is largely influenced by temperature, relative humidity, insect attack, and stress conditions of the plants.[57,324] Humidity has a determining influence on the growth rate of these degradation agents.[325]

Germination of wheat declined in storage facilities where moisture level increased with time.[326] Freshly harvested, high-moisture content grain must be dried to minimize (or prevent) excessive respiration and mold growth on grains.[327] The storage life of grain is shortened significantly when stored at warm temperatures. One day of holding warm, wet corn before drying can decrease storage life by 50%.[45]

Feng et al. (2016)[3] show humidity is rising in the Midwest in the warm season. Cook et al. (2008)[4] show that the factors leading to these humidity increases (warming Gulf of Mexico and strengthening of the Great Plains Low-Level Jet) will increase in a warming climate.

The ability of fungi to produce mycotoxins is largely influenced by temperature, relative humidity, insect attack, and stress conditions of the plants.[324] More extreme rainfall events would favor formation of Deoxynivalenol, also known as vomitoxin.[57]

Hatfield et al. (2011,[50] Table 1) give the relationships between temperature and vegetative function as well as reproductive capacity. This work was expanded and updated in Walthall et al. (2012).[328]

Mader et al. (2010)[74] report a comprehensive climate index for describing the effect of ambient temperature, relative humidity, radiation, and wind speed on environmental stress in animals. St-Pierre et al. (2003)[329] provide tables estimating economic losses in dairy due to reduced reproduction. The data show a strong gradient across the Midwest (with losses in Iowa, Illinois, and Indiana being three times the losses in Minnesota, Wisconsin, and Michigan under the current

climate). Temperature and humidity increases projected for the Midwest will increase economic losses across the entire region. Lewis and Bunter (2010)[330] document heat stress effects of temperature on pig production and reproduction.

St-Pierre et al. (2003)[329] provide tables estimating economic losses in dairy, beef, swine, and poultry, resulting in declines from both meat/milk/egg production. The data show a strong gradient across the Midwest (with losses in Iowa, Illinois, and Indiana being twice the losses in Minnesota, Wisconsin, and Michigan under the current climate). Temperature and humidity increases projected for the Midwest will increase losses across the entire region. Babinszky et al. (2011)[75] identified temperature thresholds for meat/egg/milk production, beyond which performance declines. The adverse effects of heat stress include high mortality, decreased feed consumption, poor body weight gain and meat quality in broiler chickens, and poor laying rate, egg weight, and shell quality in laying hens.[76]

Takle et al. (2013)[65] found that by mid-century, yields of corn and soybean are projected to fall well below projections based on extrapolation of trends since 1970 even under an optimistic economic scenario, with larger interannual variability in yield and total production. Liang et al. (2017)[2] report that the ratio of measured agricultural output to measured inputs would drop by an average 3% to 4% per year under medium to high emissions scenarios and could fall to pre-1980 levels by 2050 even when accounting for present rates of innovation. Schauberger et al. (2017)[66] found that the impact of exposure to temperatures from 30°C to 36°C projected for the end of the century under RCP8.5 creates yield losses of 49% for maize and 40% for soybean.

According to Easterling et al. (2017),[193] evidence suggests that droughts have become less frequent in the Midwest as the region has become wetter. However, they note that "future higher temperatures will likely lead to greater frequencies and magnitudes of agricultural droughts throughout the continental United States as the resulting increases in evapotranspiration outpace projected precipitation increases."

Major uncertainties

Global and regional climate models do not simulate well the dynamical structure of mesoscale convective systems in the Midwest, which are the critical "end processes" that create intense precipitation from increasing amounts of moisture evaporated over the Gulf of Mexico and transported by low-level jets (LLJs) into the Midwest. Secondly, the strengthening of future LLJs depends on strengthening of both the Bermuda surface high pressure and the lee surface low over the eastern Rocky Mountains. Confirming simulations of this in future climates are needed. Global and regional climate models do simulate future scenarios having increasing temperatures for the region with high confidence (a necessary ingredient for increased humidity). There is uncertainty of the temperature thresholds for crops because, as pointed out by Schauberger et al. (2017),[66] some negative impacts of higher temperatures can be overcome through increased water availability. Agricultural yield models, productivity models, and integrated assessment models each provide different ways of looking at agricultural futures, and each of these three types of models has high levels of uncertainty. However, all point to agriculture futures that fail to maintain upward historical trends.

Description of confidence and likelihood

There is *very high confidence* that increases in warm-season absolute humidity and precipitation *very likely* have eroded soils, created favorable conditions for pests and pathogens, and degraded quality of stored grain. There is *medium confidence* that projected increases in moisture, coupled with rising mid-summer temperatures, *likely* will be detrimental to crop and livestock production and put future gains in commodity grain production at risk by mid-century. Projected changes in precipitation, coupled with rising extreme temperatures, provide *medium confidence* that by mid-century Midwest agricultural productivity *likely* will decline to levels of the 1980s without major technological advances.

Key Message 2

Forestry

Midwest forests provide numerous economic and ecological benefits, yet threats from a changing climate are interacting with existing stressors such as invasive species and pests to increase tree mortality and reduce forest productivity (*likely, high confidence*). Without adaptive actions, these interactions will result in the loss of economically and culturally important tree species such as paper birch and black ash (*very likely, very high confidence*) and are expected to lead to the conversion of some forests to other forest types (*likely, high confidence*) or even to non-forested ecosystems by the end of the century (*as likely as not, medium confidence*). Land managers are beginning to manage risk in forests by increasing diversity and selecting for tree species adapted to a range of projected conditions.

Description of evidence base

Multiple ecosystem vulnerability assessments that have been conducted for major forested ecoregions within the Midwest[89,90,91,92,93] suggest that climate change is expected to have significant direct impacts to forests through effects of warming and changes in the timing and amounts of precipitation.[96,98,103,104]

Significant indirect impacts to forests are expected as warming increases the negative effects of invasive plants, insect pests, and tree pathogens of forests.[105,106] Increasing stress on individual trees from climate changes (warming temperatures, drought, and frost damage) increases the susceptibility of trees to the impacts from invasive plants, insect pests, and disease agents.[109,111]

Direct and indirect impacts of climate change may lead to the decline of culturally[88,127] and economically important tree species,[125] as well as leading to shifts in major forest types and altered forest composition as tree species at the northern limits of their ranges decline and southern species experience increasing suitable habitat.[120] These shifts raise the possibility of future losses of economic and cultural benefits of forests due to conversion to different forest types or the change to non-forest ecosystems.[119,123,124]

Many examples of land managers implementing climate adaptation in forest management exist, suggesting significant willingness to address the impacts of a changing climate across diverse land ownerships in managed forests[134] and urban forests.[133] Forest management strategies to adapt to a changing climate highlight the importance of increasing forest diversity and managing for

tree species adapted to a range of climate conditions.[8] The importance of Traditional Ecological Knowledge for informing approaches for climate adaptation on tribal lands and within ceded territory is recognized.[331]

Major uncertainties

There is significant uncertainty surrounding the ability of tree species migration rates to keep pace with changes in climate (based on temperature and precipitation) due to existing forest fragmentation and loss of habitat. Uncertainty in forest management responses, including active and widespread adaptation efforts that alter forest composition, add to the uncertainty of tree species movements. This leads to considerable uncertainty in the extent to which shifts in tree species ranges may lead to altered forest composition or loss of forest ecosystems in the future.

Due to the complex interactions among species, there is uncertainty in the extent that longer growing seasons, warming temperatures, and increased CO_2 concentrations will benefit tree species, due to both limitations in available water and nutrients, as well as limited benefits for trees relative to the positive influences of these changes on stressors (invasives, insect pests, pathogens).

Description of confidence and likelihood

There is *high confidence* that the interactions of warming temperatures, precipitation changes, and drought with insect pests, invasive plants, and tree pathogens will *likely* lead to increased tree mortality of some species, reducing productivity of some forests. There is *very high confidence* that these interactions will *very likely* result in the decline of some economically or culturally important tree species. Additionally, there is *high confidence* that suitable habitat conditions for tree species will change as temperatures increase and precipitation patterns change, making it *likely* that forest composition will be altered and forest ecosystems may shift to new forest types. Due to uncertainties on species migration rates and forest management responses to climate changes, there is *medium confidence* that by the end of the century, some forest ecosystems are *as likely as not* to convert to non-forest ecosystems.

Key Message 3

Biodiversity and Ecosystems

The ecosystems of the Midwest support a diverse array of native species and provide people with essential services such as water purification, flood control, resource provision, crop pollination, and recreational opportunities. Species and ecosystems, including the important freshwater resources of the Great Lakes, are typically most at risk when climate stressors, like temperature increases, interact with land-use change, habitat loss, pollution, nutrient inputs, and nonnative invasive species (*very likely, very high confidence*). Restoration of natural systems, increases in the use of green infrastructure, and targeted conservation efforts, especially of wetland systems, can help protect people and nature from climate change impacts (*likely, high confidence*).

Description of evidence base

Changes in climate will very likely stress many species and ecological systems in the Midwest. As a result of increases in climate stressors, which typically interact with multiple other stressors, especially in the southern half of the Midwest region, both the ecological systems and the ecological services (water purification, pollination of crops and wild species, recreational opportunities, etc.) they provide to people are at risk. We draw from a wide range of national and global scale assessments of risks to biodiversity (e.g., Maclean and Wilson 2011, Pearson et al. 2014, and the review by Staudinger et al. 2013 that covered literature included in the Third National Climate Assessment[20, 18,22]), which all agree that on the whole, we are highly likely to see increases in species declines and extinctions as a result of climate change. It is very challenging to say specifically what combination of factors will drive these responses, but the weight of evidence suggests very high confidence in the overall trends. The link to interactions with other stressors is also very strong and is described in Brook et al. (2008)[157] and Cahill et al. (2013),[17] among others. Terrestrial ecosystem connectivity, thought to be important for the adaptive capacity of many species, is very low in the southern half of the Midwest region.[158,159] This may limit the movement of species to more suitable habitats or for species from the southern United States to migrate into the Midwest. These connectivity/movement potential studies also support the idea that land-use change will constrain the potential for retaining function and overall diversity levels. The last section refers to the benefits of restoration as a mechanism for protecting people and nature from climate change impacts. While it is not possible to fully demonstrate that protection of people and nature is indeed occurring now from climate change impacts (we would need attribution of current floods, etc.), there is strong evidence that actions like restoring wetlands can reduce flooding impacts[182] and that protecting forests protects water quality and supply.

Major uncertainties

There is significant uncertainty surrounding the ability of species and ecosystems to persist and thrive under climate change, and we expect to see many different types of responses (population increases, declines, local and regional extinctions).[17] In some cases, climate change does have the potential to benefit species; for example, fish in the coldest regions of the Great Lakes (i.e., Lake Superior) are likely to show increases in productivity, at least in the short run.[332] However, as a whole, given the environmental context upon which climate change is operating, and the presence of many cold-adapted species that are close to the southern edge of their distributional range, we expect more declines than increases.

The last section of the Key Message focuses on land protection and restoration—conservation strategies intended to reduce the impacts of land-use change. Many modeling studies have called out loss of habitat in the Midwest as a key barrier to both local survival and species movement in response to climate change (Schloss et al. 2012 and Carroll et al. 2015 are two of the most recent[158,159]). Restoring habitat can restore connectivity and protect key ecological functions like pollination services and water purification. Restoring wetlands also can help protect ecosystems and people from flooding, which is the rationale for the last line in the Key Message.

Description of confidence and likelihood

In the Midwest, we already have seen very high levels of habitat loss and conversion, especially in grasslands, wetlands, and freshwater systems. This habitat degradation, in addition to the

pervasive impacts of invasive species, pollution, water extraction, and lack of connectivity, all suggest that the adaptive capacity of species and systems is compromised relative to systems that are more intact and under less stress. Over time, this pervasive habitat loss and degradation has contributed to population declines, especially for wetland, prairie, and stream species. A reliance on cold surface-water systems, which often have compromised connectivity (due to dams, road-stream crossings with structures that impede stream flow, and other barriers) suggests that freshwater species, especially less mobile species like mussels, which are already rare, are at particular risk of declines and extinction. Due to the variety of life histories and climate sensitivities of species within the region, it is very challenging to specify what mechanisms will be most important in terms of driving change. However, knowing that drivers like invasive species, habitat loss, pollution, and hydrologic modifications promote species declines, it is *very likely* that the effects of climate change will interact, and we have *very high confidence* that these interactions will tend to increase, rather than decrease, stresses on species that are associated with these threats. While there is strong evidence that investments in restoring habitat can benefit species, we currently do not have strong observational evidence of the use of these new habitats, or benefits of restored wetlands, in response to isolated climate drivers. Thus, the confidence level for this statement is lower than for the first half of the message.

Key Message 4

Human Health

Climate change is expected to worsen existing conditions and introduce new health threats by increasing the frequency and intensity of poor air quality days, extreme high temperature events, and heavy rainfalls; extending pollen seasons; and modifying the distribution of disease-carrying pests and insects (*very likely, very high confidence*). By mid-century, the region is projected to experience substantial, yet avoidable, loss of life, worsened health conditions, and economic impacts estimated in the billions of dollars as a result of these changes (*likely, high confidence*). Improved basic health services and increased public health measures—including surveillance and monitoring—can prevent or reduce these impacts (*likely, high confidence*).

Description of evidence base

There is strong evidence that increasing temperatures and precipitation in the Midwest will occur by the middle and end of the 21st century.[27] The impacts of these changes on human health are broadly captured in the 2016 U.S. Global Change Research Program's Climate and Health Assessment.[26] Air quality, including particulate matter and ground-level ozone, is positively associated with increased temperatures and has been well-documented to show deleterious impacts on morbidity and mortality.[231] Likewise, increased temperatures have been shown in communities in the Midwest, as well as across the United States, to have substantial impacts on health and well-being.[232,233,235,236,333,334] The frequency of extreme rainfall events in the Midwest has increased in recent decades, and this trend is projected to continue.[193] Studies have shown that extreme rainfall events lead to disease, injury, and death.[237] Increases in seasonal temperatures and shifting precipitation patterns have been well documented to be correlated with increased pollen production, allergenicity, and pollen season length.[230,231] Similarly, there is agreement that shifting temperature and precipitation patterns are making habitats more suitable for disease-carrying vectors to move

northward toward the Midwest region.[242,243,250,335,336,337] The disease burden and economic projections primarily are based on EPA estimates.[28]

Access to basic preventive care measures quantifiably reduces disease burden for climate-sensitive exposures.[238,240] Gray literature indicates that public health practitioners are dedicated to increasing capacity for adapting to climate change through classic public health activities such as conducting vulnerability assessments, employing communication and outreach campaigns, and investing in surveillance efforts.[26,244,245,246,247,248]

Major uncertainties

While the modeling performed by the EPA was completed using the best available information, there is uncertainty around the extent to which biophysical adaptations will protect midwestern populations from heat-, air pollution-, aeroallergen-, and vector-related illness and death. Likewise, while there is a general consensus regarding habitat suitability for disease-carrying vectors in the eastern and western United States, the degree to which the disease burden may increase or decrease is largely uncertain.

Description of confidence and likelihood

Based on the evidence, there is *very high confidence* that climate change is *very likely* to impact midwesterners' health.

Key Message 5

Transportation and Infrastructure

Storm water management systems, transportation networks, and other critical infrastructure are already experiencing impacts from changing precipitation patterns and elevated flood risks (*medium confidence*). Green infrastructure is reducing some of the negative impacts by using plants and open space to absorb storm water (*medium confidence*). The annual cost of adapting urban storm water systems to more frequent and severe storms is projected to exceed $500 million for the Midwest by the end of the century (*medium confidence*).

Description of evidence base

The patterns of increased annual precipitation, and the size and frequency of heavy precipitation events in the Midwest, are shown in numerous studies and highlighted in Melillo et al. (2014)[27] and Easterling et al. (2017).[193] Increases in annual precipitation of 5% to 15% are reported across the Midwest region.[193] In addition, both the frequency and the intensity of heavy precipitation events in the Midwest have increased since 1901.[193]

For the early 21st century (2016–2045), both lower and higher scenarios (RCP4.5 and RCP8.5) indicate that average annual precipitation could increase by 1% to 5% across the Midwest, suggesting that the observed increases are likely to continue. By mid-century (2036–2065), both scenarios (RCP4.5 and RCP8.5) indicate precipitation increases of 1% to 5% in Missouri and Iowa and 5% to 10% increases in states to the north and east. By late century (2070–2089), precipitation is expected to increase by 5% to 15% over present day, with slightly larger increases in the higher scenario (RCP8.5). Model simulations suggest that most of these increases will occur in winter and spring

over the 21st century. Similar to annual precipitation, the amounts from the annual maximum one-day precipitation events (a measure of heavy precipitation events) are projected to increase over time in the Midwest. The size of the events could increase by 5% to 15% by late century.[193]

Gray literature documents that heavy rains in the Midwest are overwhelming storm water management systems, leading to property damage. Kenward et al. (2016)[256] provide examples of rain-related sewage overflows in the Midwest. These include an overflow of 681 million gallons during heavy rains in April 2015 in Milwaukee and an overflow of over 100 million gallons from December 26–28, 2015, in St. Louis. Winters et al. (2015)[37] document that failure of storm water management systems in heavy rain leads to property damage, including basement backups.

The disruption of transportation networks by heavy precipitation in the Midwest has been documented by collecting contemporary news reports and by compiling state government reports. Posey (2016)[338] relates that four storms between April 2013 and April 2014 forced evacuations or damaged cars in St. Louis, Missouri. In the same period, there were 18 flood-related closures on Missouri roads, a figure that excludes closures on small local roads. Flooding in May 2017 led to the closure of more than 400 roads across Missouri, a figure that again excludes local roads. Closed roadways included multiple stretches of Interstate 44, as well as sections of I-55, affecting interstate traffic between St. Louis and Memphis.[339] News reports document that the same stretch of I-44 was shut down during the floods of December 2015–January 2016.[340]

Flood-related disruptions to Midwest barge and rail traffic in 2013 were documented by several articles in *Journal of Commerce*, a shipping trade magazine.[265,266] *WorkBoat*, a trade journal of the inland shipping industry, documents that Mississippi River navigation has been halted by flooding in 2013, 2015, 2016, and 2017. It also documents low river conditions affecting navigation in 2012 and 2015.[267,268,269,270,341] Disruptions to rail service caused by the floods of 2017 were documented in news media accounts.[342] Changon (2009)[343] documents that flooding in 2008 resulted in extensive damage to railroads in Illinois and adjacent states, with costs exceeding $150 million due to direct damage and lost revenue.

Although there is ample documentation of transportation systems in the Midwest being disrupted by floods in recent years, there is a lack of long-term time series data on disruptions with which to determine whether these incidents are becoming more frequent. Development of long-term data on transportation disruptions in the Midwest is a research need. It is clear that flood frequency and severity on major rivers in the Midwest have increased in recent decades, although additional research is needed on the relative contributions of climate change and land-use change to increases in flood risk.[344,345,346]

The EPA estimated economic costs related to infrastructure and transportation in the Midwest, including costs associated with bridge scour and pavement degradation.[28] The use of green infrastructure to reduce impacts associated with heavy precipitation is also documented in gray literature, including municipal planning documents. Using planted areas to absorb rainfall and reduce runoff has become a common approach to storm water management.[223,275,276,347,348,349,350] Dechannelization and restoration of streams as a technique for improving storm water management is described in Trice (2013)[282] and Milwaukee Metropolitan Sewer District (2017).[281] Preservation of open space is described in Ducks Unlimited (2017)[279] and the Ozaukee Washington

Land Trust (2016).[280] The use of urban forestry as an adaptation method is documented in the Minneapolis Marq2 Project (2017)[277] and the Cleveland Tree Plan (2015).[278] Projected costs to storm water systems are based on EPA projections.[28]

Major uncertainties

Although there is *very high confidence* that flood risk is increasing in the Midwest, there remains uncertainty about the relative contributions of climate change and land-use change. There is, however, sufficient evidence that changing precipitation patterns are leading to changes in hydrology in the Midwest,[351,352,353,354,355] and that heavier precipitation patterns are consistent with projections from climate models, to justify a rating of *medium confidence* to the assertion that climate change is contributing to changes in flooding risk. There is *high confidence* that local governments and nongovernmental organizations are turning to green infrastructure solutions as a response to increased flooding risk. Additional research is needed to quantify the aggregate benefits of these approaches.

While it is clear that flood frequency and severity on major rivers in the Midwest have increased in recent decades, it must be emphasized that the change in precipitation levels is not the only factor contributing to the increase in flood risk. Land-use change, particularly the destruction of floodplains by levee systems, has also been documented as a key contributor to increasing flood risk in the Midwest.[344,345,346] On smaller streams, tile drainage systems have been shown to exacerbate flood risk.[24] Determining the relative contribution of land-use change and climate change to increases in riverine flood risk is an important research need.

Description of confidence and likelihood

There is *medium confidence* that climate change is contributing to increased flood risk in the Midwest; there is *medium confidence* that green infrastructure is reducing flood risk. There is much uncertainty associated with specific numerical projections. This leads to *medium confidence* that costs will exceed $500 million. However, the EPA projections are sufficient to provide *high confidence* that increasing the capacity of existing storm water systems in order to maintain current levels of service would require significant expenditures on the part of urban sewer districts.

Key Message 6

Community Vulnerability and Adaptation

At-risk communities in the Midwest are becoming more vulnerable to climate change impacts such as flooding, drought, and increases in urban heat islands (*as likely as not, high confidence*). Tribal nations are especially vulnerable because of their reliance on threatened natural resources for their cultural, subsistence, and economic needs (*likely, medium confidence*). Integrating climate adaptation into planning processes offers an opportunity to better manage climate risks now (*medium confidence*). Developing knowledge for decision-making in cooperation with vulnerable communities and tribal nations will help to build adaptive capacity and increase resilience (*high confidence*).

Description of evidence base

Limited evidence in the scientific literature indicates that at-risk communities in the Midwest will be increasingly vulnerable to the impacts of climate change, including increased flooding resulting from increased variation in precipitation patterns and changing lake levels,[285] urban heat islands,[287] and an intensification of heat and drought (see also the impacts and associated references in the previous sections).[286]

Several recent survey reports[28,283,284] project negative climate impacts for tribal nations and Indigenous communities, especially as a result of an increased frequency of extreme precipitation events.[283] Tribal nations are especially vulnerable to climate impacts because of their reliance on natural resources,[127] the isolation of rural communities, and potential shifts of species out of sovereign land.[309,310] Climate change thus poses a threat to tribal culture, sovereignty, health, and way of life.[39]

Gray literature,[293] survey reports,[32] and scientific literature[292] point to a few initiatives to integrate adaptation into municipal planning processes and utilize participatory methodologies to evaluate and manage climate risk.

A growing body of research indicates that interaction between producers of climate information, intermediaries, and end users plays a critical role in increasing climate knowledge integration and use for adaptation in the Midwest.[224,294,300,308] Limited evidence links the implementation of adaptation actions identified as a result of these collaborations to reduced sensitivity.[304,305,306]

Major uncertainties

Limited research specific to the Midwest region contributes to uncertainty around the specific vulnerabilities of at-risk communities, including urban and rural communities and tribal nations. Though climate change planning and action in both Midwest cities and rural areas are underway, documentation remains low, few examples exist in the public literature of the failure or success of efforts to mainstream climate action into municipal governance, and attempts to assess vulnerabilities, especially in poor urban communities, frequently encounter climate justice barriers. Likewise, the number, scope, and nature of tribal adaptation plans remain undocumented, as does the degree of implementation of these plans and the manner in which Traditional Ecological Knowledge is incorporated.

Description of confidence and likelihood

There is *high confidence* that communities in the Midwest will *as likely as not* be increasingly vulnerable to climate change impacts such as flooding, urban heat islands, and drought. Similarly, there is *medium confidence* that tribal nations in the Midwest are *likely* to be especially vulnerable because of their reliance on threatened natural resources for their cultural, subsistence, and economic needs. Due to limited documentation in the literature, there is *medium confidence* that integrating adaptation into planning processes will offer an opportunity to manage climate risk better. Finally, there is *high confidence* that developing knowledge for decision-making in cooperation with vulnerable communities and tribal nations will help to decrease sensitivity and build adaptive capacity.

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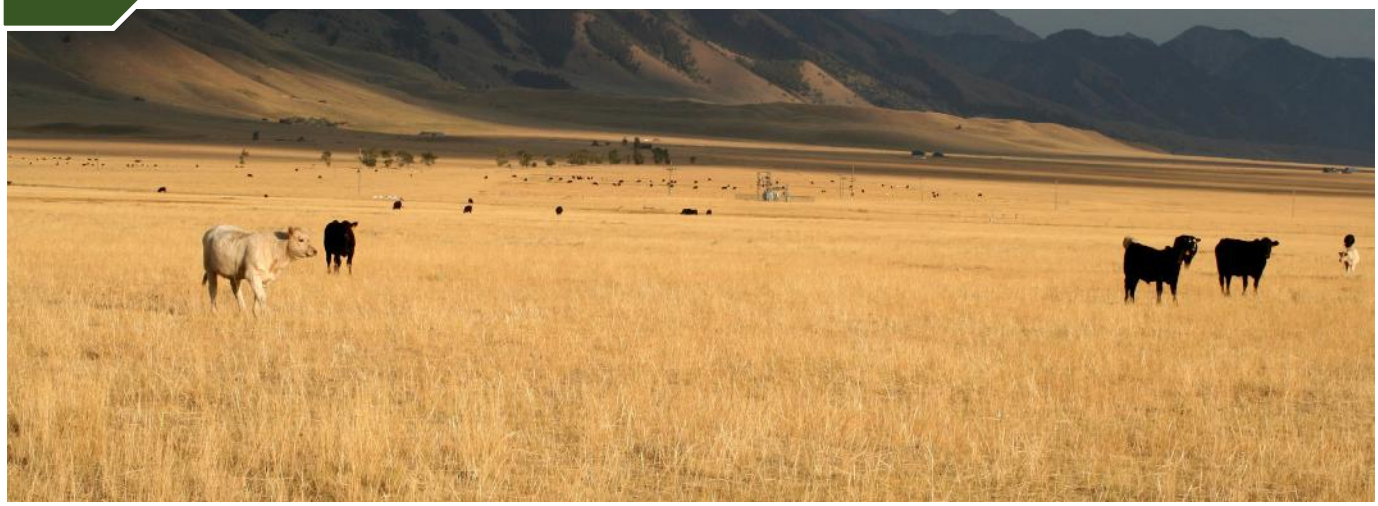

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Key Message 1

Water

Water is the lifeblood of the Northern Great Plains, and effective water management is critical to the region's people, crops and livestock, ecosystems, and energy industry. Even small changes in annual precipitation can have large effects downstream; when coupled with the variability from extreme events, these changes make managing these resources a challenge. Future changes in precipitation patterns, warmer temperatures, and the potential for more extreme rainfall events are very likely to exacerbate these challenges.

Key Message 2

Agriculture

Agriculture is an integral component of the economy, the history, and the culture of the Northern Great Plains. Recently, agriculture has benefited from longer growing seasons and other recent climatic changes. Some additional production and conservation benefits are expected in the next two to three decades as land managers employ innovative adaptation strategies, but rising temperatures and changes in extreme weather events are very likely to have negative impacts on parts of the region. Adaptation to extremes and to longer-term, persistent climate changes will likely require transformative changes in agricultural management, including regional shifts of agricultural practices and enterprises.

Key Message 3

Recreation and Tourism

Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are at risk in a changing climate. Rising temperatures have already resulted in shorter snow seasons, lower summer streamflows, and higher stream temperatures and have negatively affected high-elevation ecosystems and riparian areas, with important consequences for local economies that depend on winter or river-based recreational activities. Climate-induced land-use changes in agriculture can have cascading effects on closely entwined natural ecosystems, such as wetlands, and the diverse species and recreational amenities they support. Federal, tribal, state, and private organizations are undertaking preparedness and adaptation activities, such as scenario planning, transboundary collaboration, and development of market-based tools.

Key Message 4

Energy

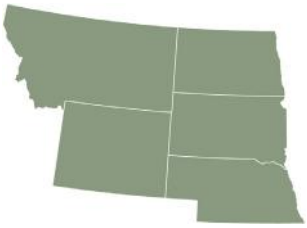
Fossil fuel and renewable energy production and distribution infrastructure is expanding within the Northern Great Plains. Climate change and extreme weather events put this infrastructure at risk, as well as the supply of energy it contributes to support individuals, communities, and the U.S. economy as a whole. The energy sector is also a significant source of greenhouse gases and volatile organic compounds that contribute to climate change and ground-level ozone pollution.

Key Message 5

Indigenous Peoples

Indigenous peoples of the Northern Great Plains are at high risk from a variety of climate change impacts, especially those resulting from hydrological changes, including changes in snowpack, seasonality and timing of precipitation events, and extreme flooding and droughts as well as melting glaciers and reduction in streamflows. These changes are already resulting in harmful impacts to tribal economies, livelihoods, and sacred waters and plants used for ceremonies, medicine, and subsistence. At the same time, many tribes have been very proactive in adaptation and strategic climate change planning.

Executive Summary



In the Northern Great Plains, the timing and quantity of both precipitation and runoff have important consequences for water supplies, agricultural activities, and energy production. Overall, climate projections suggest that the number of heavy precipitation events (events with greater than 1 inch per day of rainfall) is projected to increase. Moving forward, the magnitude of year-to-year variability overshadows the small projected average decrease in streamflow. Changes in extreme events are likely to overwhelm average changes in both the eastern and western regions of the Northern Great Plains. Major flooding across the basin in 2011 was followed by severe drought in 2012, representing new and unprecedented variability that is likely to become more common in a warmer world.

The Northern Great Plains region plays a critical role in national food security. Among other anticipated changes, projected warmer and generally wetter conditions with elevated atmospheric carbon dioxide concentrations are expected to increase the abundance and competitive ability of weeds and invasive species,[1,2] increase livestock production and efficiency of production,[3] and result in longer growing seasons at mid- and high latitudes.[4,5] Net primary productivity, including crop yields[6] and forage production,[7,8] is also likely to increase, although an increasing number of extreme temperature events during critical pollination and grain fill periods is likely to reduce crop yields.[9]

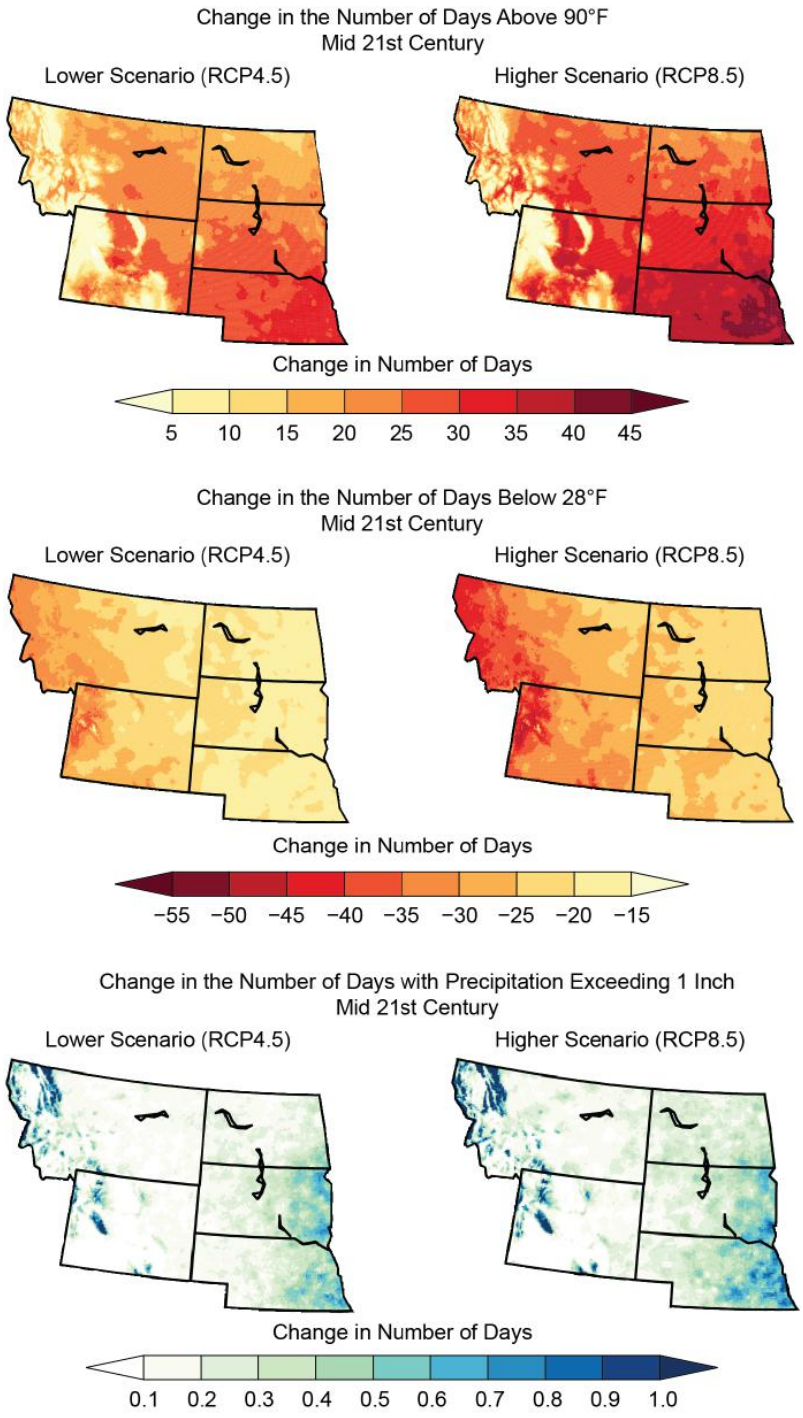
Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are ingrained in the region's cultures. Higher temperatures, reduced snow cover, and more variable precipitation will make it increasingly challenging to manage the region's valuable wetlands, rivers, and snow-dependent ecosystems. In the mountains of western Wyoming and western Montana, the fraction of total water in precipitation that falls as snow is expected to decline by 25% to 40% by 2100 under a higher scenario (RCP8.5),[10] which would negatively affect the region's winter recreation industry.[11] At lower-elevation areas of the Northern Great Plains, climate-induced land-use changes in agriculture can have cascading effects on closely entwined natural ecosystems, such as wetlands,[12] and the diverse species and recreational opportunities they support.

Energy resources in the Northern Great Plains include abundant crude oil, natural gas, coal, wind, and stored water, and to a lesser extent, corn-based ethanol, solar energy, and uranium. The infrastructure associated with the extraction, distribution, and energy produced from these resources is vulnerable to the impacts of climate change. Railroads and pipelines are vulnerable to damage or disruption from increasing heavy precipitation events and associated flooding and erosion.[13] Declining water availability in the summer would likely increase costs for oil production operations, which require freshwater resources.[13] These cost increases will either lead to lower production or be passed on to consumers. Finally, higher maximum temperatures, longer and more severe heat waves, and higher overnight lows are expected to increase electricity demand for cooling in the summer, further stressing the power grid.[13]

Indigenous peoples in the region are observing changes to climate, many of which are impacting livelihoods as well as traditional subsistence and wild foods, wildlife, plants and water for ceremonies, medicines, and health and well-being.[14,15,16,17,18,19,20,21,22,23,24,25,26] Because some tribes and Indigenous peoples are among those in the region with the highest rates of poverty and unemployment, and because many are still

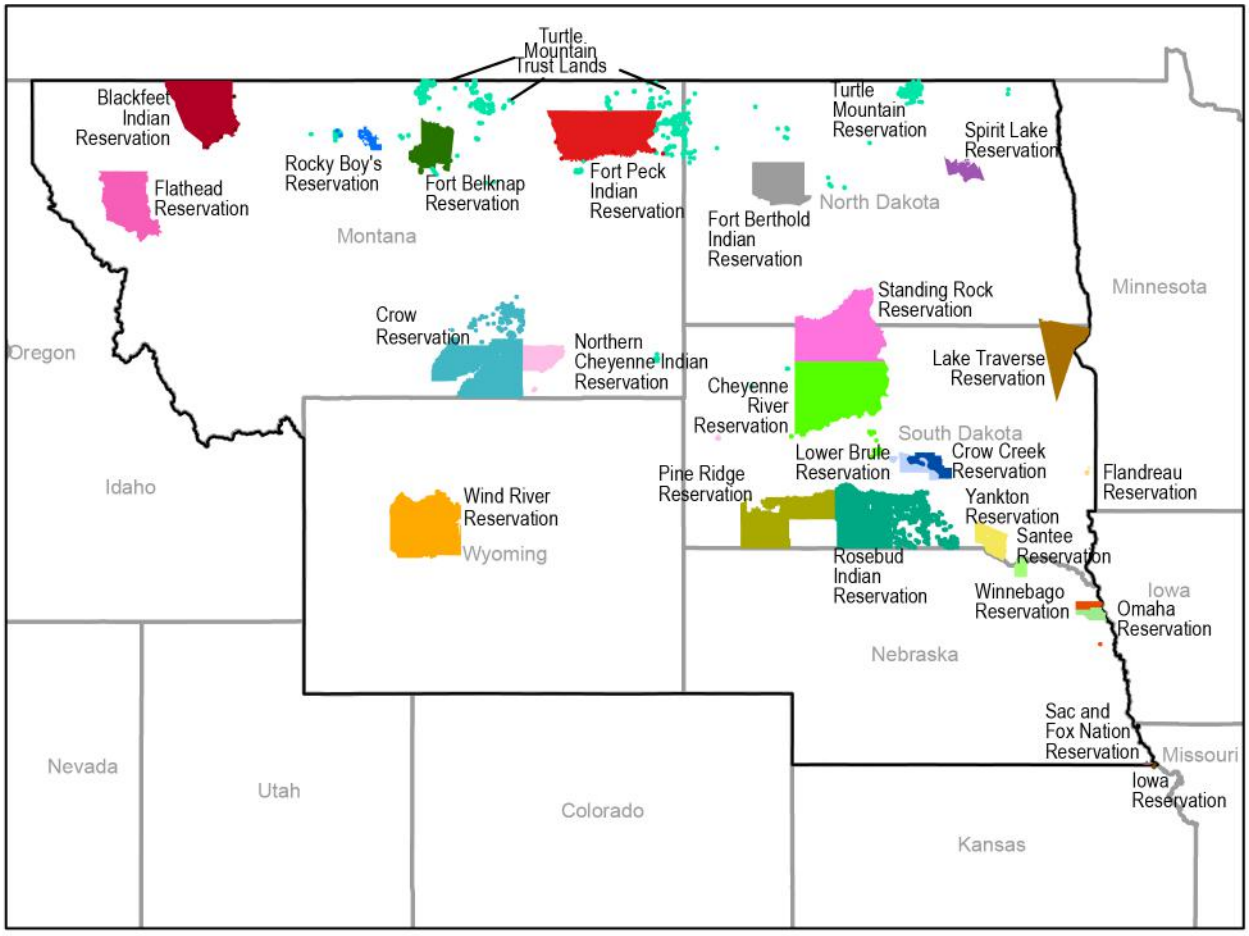
directly reliant on natural resources, they are among the most at risk to climate change (e.g., Gamble et al. 2016, Cozzetto et al. 2013, Espey et al. 2014, Wong et al. 2014, Kornfeld 2016, Paul and Caplins 2016, Maynard 2014, USGCRP 2017[18,24,25,27,28,29,30,31]).

Projected Changes in Very Hot Days, Cool Days, and Heavy Precipitation



Projected changes are shown for (top) the annual number of very hot days (days with maximum temperatures above 90°F, an indicator of crop stress and impacts on human health), (middle) the annual number of cool days (days with minimum temperatures below 28°F, an indicator of damaging frost), and (bottom) heavy precipitation events (the annual number of days with greater than 1 inch of rainfall; areas in white do not normally experience more than 1 inch of rainfall in a single day). Projections are shown as changes from the 1976–2005 average for the middle of the 21st century (2036–2065) for the lower and higher scenarios (RCP4.5 and RCP8.5). *From Figure 22.2 (Sources: NOAA NCEI and CICS-NC)*.

Northern Great Plains Tribal Lands



The map outlines reservation and off-reservation tribal lands in the Northern Great Plains, which shows where the 27 federally recognized tribes have a significant portion of lands throughout the region. Information on Indigenous peoples' climate projects within the Northern Great Plains is described in Chapter 15: Tribes and Indigenous Peoples. *From Figure 22.7 (Sources: created by North Central Climate Science Center [2017] with data from the Bureau of Indian Affairs, Colorado State University, and USGS National Map)*.

Background

The Northern Great Plains has three distinct regional geographic features associated with a strong east-to-west gradient of decreasing precipitation and a stark rise in elevation at the montane western boundary. The eastern edge of the region includes a humid-continental climate and the Red River Valley, where the capacity to store water is often exceeded, leading to extensive flooding. A large swath of the central Northern Great Plains falls within the Upper Missouri River Basin. Much of this basin is arid to semiarid, and because temperatures and rates of evapotranspiration (the evaporation of water from the soil and transpiration from plants) are so high, only 9% of precipitation ultimately reaches the Missouri River as runoff. For comparison, other basins in the United States yield more than 40% runoff. In the mountainous far western part of the region, including central and western Wyoming and Montana, water dynamics are driven by large seasonal snowpack that accumulates in winter and early spring and provides critical resources for non-montane areas through runoff during the warm season.

These intraregional gradients in precipitation, temperature, and water availability drive east–west differences in land use and climate. The eastern portion of the region is characterized by rainfed row crop agriculture and is often subject to flooding. For example, Devils Lake in North Dakota is a closed basin, meaning that it has no natural outflows. The basin is often so full that it is prone to flooding the communities around it. Separately, the irrigated cropland and grazing lands in the central portion of the Northern Great Plains are critical for U.S. livestock production, yet the arid to semiarid climate is highly variable from year to year, which makes it difficult to manage agriculture, recreation, and cultural resources. The western portion of the region is devoted primarily to native ecosystems used for grazing and recreation, but dryland cropping is also important, and forestry is important in the far-western edge of the region. Coal, oil, and natural gas are produced throughout the Northern Great Plains.

The highly variable climate of the Northern Great Plains poses challenges for the sustainable use of water, land, and energy resources by competing urban, suburban, rural, and tribal populations. Climate change is expected to exacerbate those challenges, which include 1) effectively managing both overabundant and scarce water resources, 2) supporting adaptation of sustainable agricultural systems, 3) fostering conservation of ecosystems and cultural and recreational amenities, 4) minimizing risk to energy infrastructure that is vulnerable to climate change and extreme weather events, and 5) mitigating climate impacts to vulnerable populations.

Diverse land uses across the region are overlain with a quilt work of private, state, federal, tribal, and other land ownership. Many of these institutions foster adaptation to existing climatic variability (Figure 22.1). For example, the Missouri Headwaters Drought Resilience Demonstration Project was launched in July 2014 to demonstrate how federal, state, and local stakeholders can work together to build long-term drought resilience. The project leverages federal and state resources and engages communities in the development and implementation of local watershed drought resilience plans and activities. Led by the Montana Department of Natural Resources and Conservation, more than 10 federal agencies, 20 watershed groups, and 14 nongovernmental organizations are contributing to the project (see Missouri Headwaters Drought Resilience Demonstration Project 2015[32]). It is a replicable model that is producing concrete, on-the-ground results, including tools for drought monitoring, assessment, and forecasting. In another example,

Climate Change Impacts and Adaptation Across the Northern Great Plains

1

Impact: Flash droughts and high heat events illustrate challenges for sustainability of ranching operations, with emergent impacts on rural prosperity and mental health.

Response: Adaptive management frameworks, developed through management–science partnerships, proactively increase flexibility in operational decision-making to reduce economic and ecological risk.

2

Impact: Consecutive years of drought across the region force ranchers to consider selling off their herds.

Response: Montana's Matador Ranch establishes a "grassbank" that allows local ranchers to pay discounted fees for access to additional grass during droughts in exchange for wildlife-friendly practices on their own operations.

3

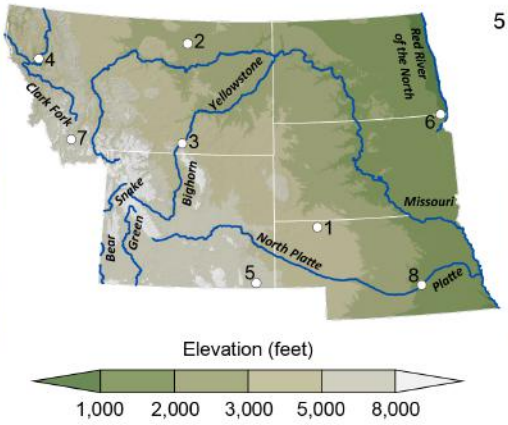
Impact: Rising temperatures hasten the spread of invasive species in riparian ecosystems, threatening culturally significant native species and food sources in the Crow Indian (Apsaalooké) Reservation.

Response: The USDA NRCS Crow Agency worked with Little Big Horn College students to remove invasive populations along the Little Big Horn River. They also revegetated plains cottonwood in sandbars and developed riparian buffer zones.

4

Impact: Anticipated climate change impacts on cultural resources raise concerns within the leadership of the Confederated Salish and Kootenai Tribes.

Response: Tribal leaders developed their climate change strategic plan to address climate impacts and vulnerabilities drawing heavily on Traditional Ecological Knowledge.



5

Impact: Greenhouse gas emissions from petroleum and natural gas production across the Northern Great Plains are among the highest in the Nation.

Response: Potential wind energy resources are among the largest in the Northern Great Plains.

6

Impact: The Prairie Pothole Region, considered the world's most productive habitat for waterfowl, is threatened by warming temperatures.

Response: The Prairie Pothole Joint Venture implements wetland and grassland protection, restoration, and enhancement projects to sustain populations of waterfowl, shorebirds, and prairie landbirds.

7

Impact: Changing runoff characteristics and increasing stream temperatures threaten water and ecological resources.

Response: The Beaverhead Drought Resiliency Plan was written to improve preparedness by reducing vulnerabilities to future drought events.

8

Impact: Increased growing season length and greater variability in temperature and precipitation stress critically important natural resources.

Response: The Platte Basin Timelapse project (PBT) uses time-lapse photography and multimedia storytelling to document life across the Platte River watershed.

Figure 22.1: The Northern Great Plains exhibits a high amount of geographical, ecological, and climatological variability, in part because of the dramatic elevation change across the region. The impacts of climate change throughout the Northern Great Plains include changes in flooding and drought, rising temperatures, and the spread of invasive species. Ranchers, tribal communities, universities, government institutions, and other stakeholders from across the region have taken action to confront these challenges. Photo credits: 1) Justin Derner, USDA Agricultural Research Service, 2) Kenton Rowe Photography, 3) Kurrie Jo Small, 4) Eugene Wilson (CC BY-NC 2.0), 5) Jacob Byk, 6) Benjamin Rashford, 7) Chris Carparelli, 8) Mariah Lundgren, University of Nebraska Platte Basin Timelapse Project.

Nebraska completed a statewide climate change assessment report in 2014.[33] Officials were then able to use this report to convene eight sector-based roundtable discussions in 2015, engaging more than 350 people, to identify a suite of key issues, strategies, and next steps to help develop a statewide climate change action plan.[34]

Key Message 1

Water

Water is the lifeblood of the Northern Great Plains, and effective water management is critical to the region's people, crops and livestock, ecosystems, and energy industry. Even small changes in annual precipitation can have large effects downstream; when coupled with the variability from extreme events, these changes make managing these resources a challenge. Future changes in precipitation patterns, warmer temperatures, and the potential for more extreme rainfall events are very likely to exacerbate these challenges.

Streamflow in the Northern Great Plains is driven by a number of factors. Because the Northern Great Plains is so far from the coasts and the modulating effect of the oceans, the regional climate system is prone to dramatic climate variability. The Upper Missouri River Basin (the region's primary surface water feature spanning all five states) is very sensitive to climatic fluctuations, resulting in extreme drought or flooding events roughly every decade over the past century.[35] The timing and quantity of both precipitation and runoff have important consequences for water supplies, agricultural activities, and energy production. Parts of the region are among the most arid in the Nation—for example, less than 10% of regional precipitation reaches streams and the Missouri River[36]—so relatively small changes in annual precipitation can produce large changes in runoff. High evaporation rates result in lower soil moisture and streamflow in the region relative to more humid parts of the country. Trends in annual runoff across the region over the past 50 years show a distinct east–west difference where the western portions show a decrease and eastern areas show an increase.[37] Soil moisture and snowpack have a major impact on streamflow, and as a result of these factors combined with variability in precipitation, the amount of annual streamflow can vary by as much as a factor of three from year to year.[35] In the western montane portion of the region, 39 glaciers contribute to streamflows through their seasonal melt process. These glaciers are experiencing sustained loss,[38] and, like global glacier losses over recent decades, local glacier losses are attributable to higher temperatures.[39,40] Glacier flows are critically important for local watersheds and ecosystems; however, their contribution to the entire Upper Missouri River Basin is very small. High variability in the proportion of precipitation that reaches streams in a given year, coupled with a relatively high frequency of extreme events (for example, heavy rainfall events and droughts), makes managing climate change impacts on water resources challenging. Major flooding across the basin in 2011 was followed by severe drought in 2012, representing new and unprecedented variability that is likely to become more common in a warmer world.

Given the losses in important snowpack water storage, reservoirs and groundwater represent critical buffers to climate impacts, since they have large storage capacity that can be filled during wet periods and withdrawn during dry periods. Evaporation rates exceed 100% of precipitation in some cases,[41] which results in a deficit of surface water and thus reliance upon groundwater. Groundwater and aquifer recharge rates[42] are relatively high in the region (including parts of Wyoming, South Dakota, Montana, and Nebraska) and seem sustainable given current rates of groundwater extraction.

Projected Changes in Very Hot Days, Cool Days, and Heavy Precipitation

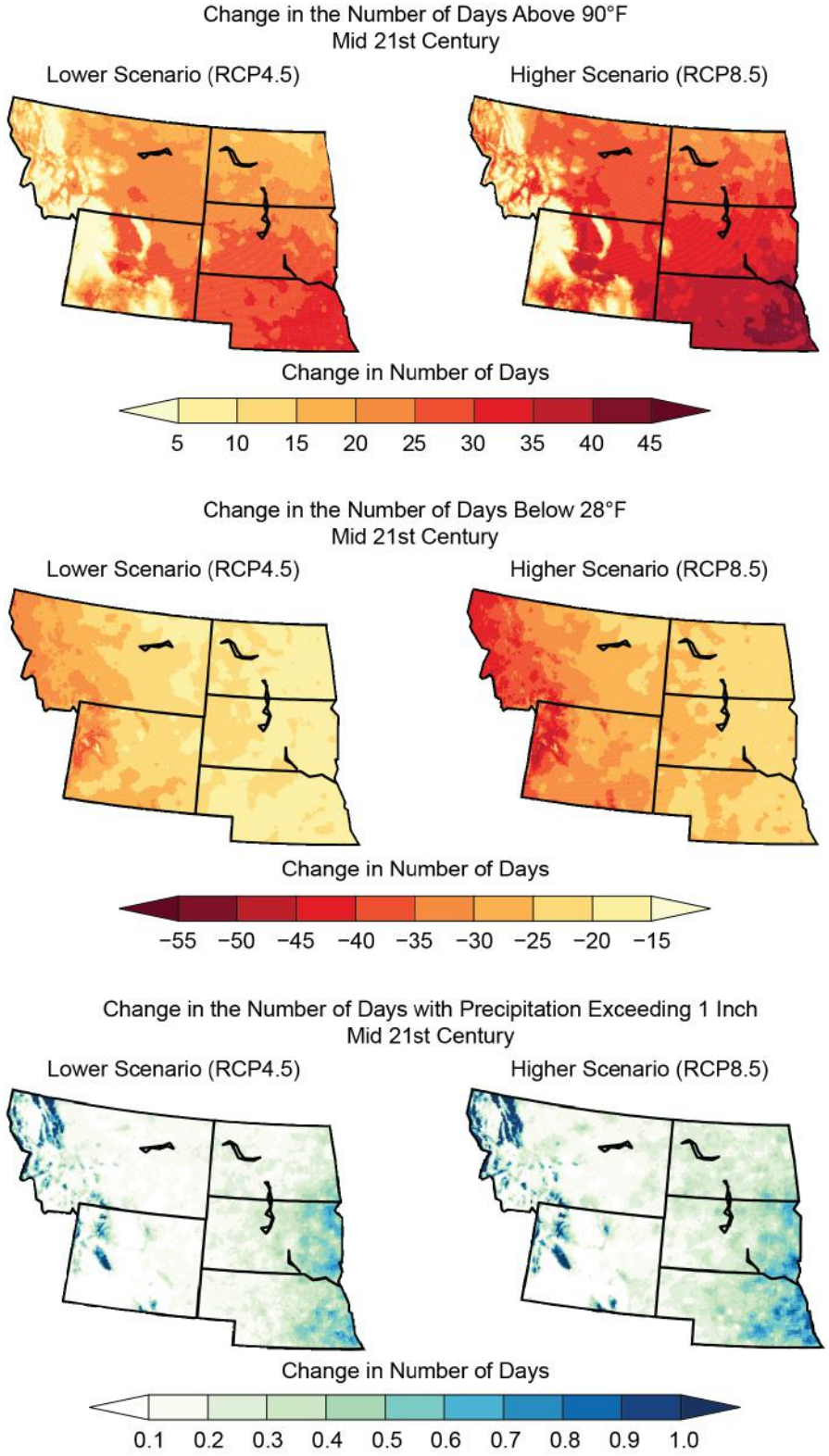


Figure 22.2: Projected changes are shown for (top) the annual number of very hot days (days with maximum temperatures above 90°F, an indicator of crop stress and impacts on human health), (middle) the annual number of cool days (days with minimum temperatures below 28°F, an indicator of damaging frost), and (bottom) heavy precipitation events (the annual number of days with greater than 1 inch of rainfall; areas in white do not normally experience more than 1 inch of rainfall in a single day). Projections are shown as changes from the 1976–2005 average for the middle of the 21st century (2036–2065) for the lower and higher scenarios (RCP4.5 and RCP8.5). Sources: NOAA NCEI and CICS-NC.

Hydrologic Changes Across the Northern Great Plains

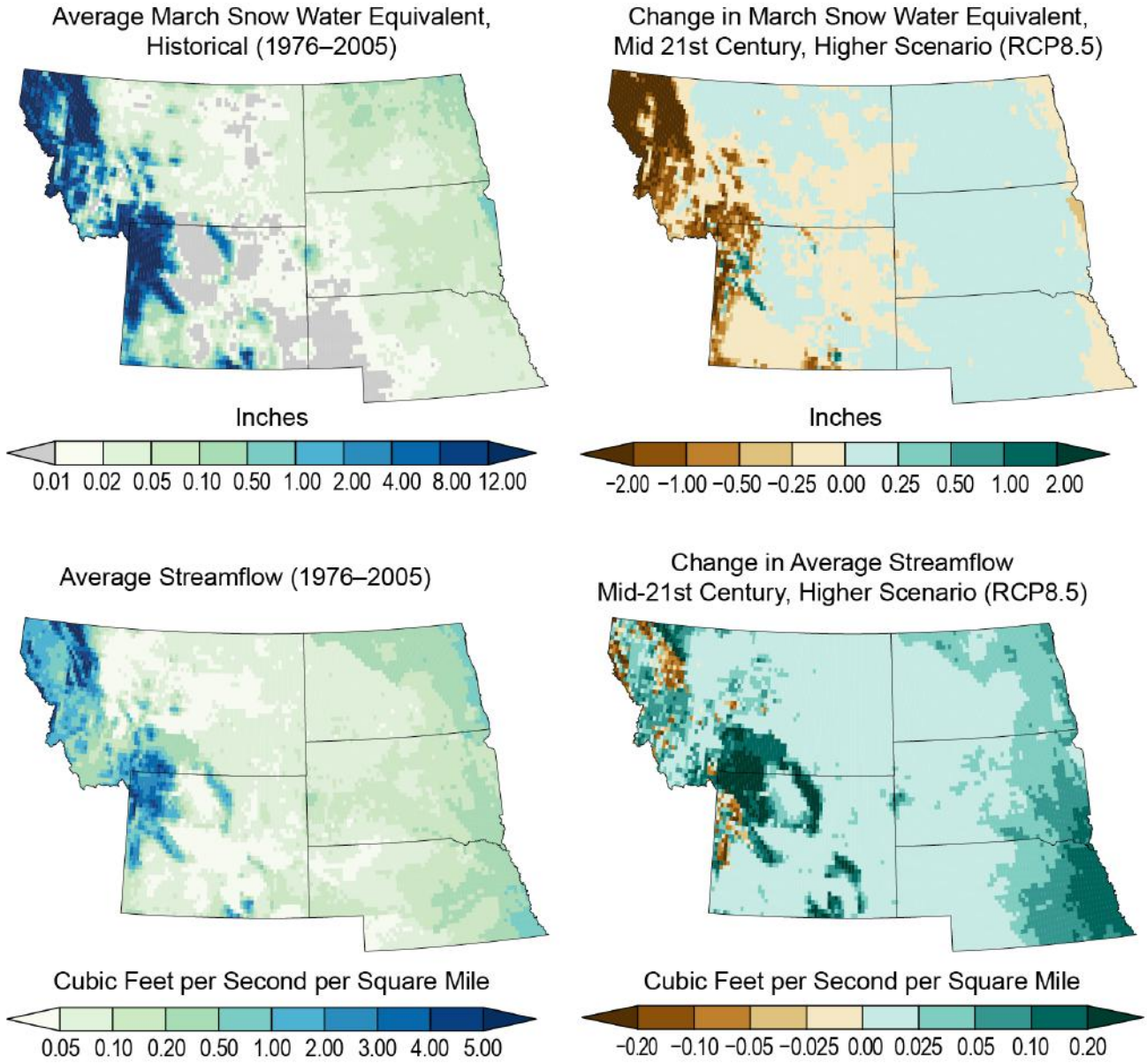


Figure 22.3 These maps show historical (left; 1976–2005) and projected changes (right; 2036-2065) under a higher scenario (RCP8.5) in average snowpack (top row) and annual streamflow (bottom row). Snowpack is measured in terms of snow water equivalent, or SWE—the depth in inches of the amount of water contained in the snowpack. The top two maps show average values for March to provide historical and future end-of-season estimates of SWE. This illustrates projected warming and potential snow loss. Projected decreases in snowpack across montane western regions in the upper-right plot are primarily the result of projected warming at the highest elevations. Projected increases in snow at lower elevations are less important, since those changes are relative to a much lower average (top left) than in montane regions. Similarly, annual streamflows are expected to increase across much of the eastern part of the region, with isolated but important decreases in the western highlands. In this context, streamflow refers to the sum of surface runoff and subsurface flow for each location in space. Sources: NOAA NCEI and CICS-NC.

Climate model projections paint a clear picture of a warmer future in the Northern Great Plains, with conditions becoming consistently warmer in two to three decades and temperatures rising steadily towards the middle of the century, irrespective of the scenario selected (Figure 22.2). This warming is projected to occur in conjunction with less snowpack and a mix of increases and reductions in the average annual water availability (Figure 22.3). Precipitation and streamflow projections show only modest changes, but many areas within

the region are already subject to a high degree of year-to-year variability—both wet and dry years. Low-probability, but high-severity and high-impact, events are the result of large variability, including both extreme flood events like in 2011 and drought events like in 2012. This interannual variability implies greater uncertainty about future climate and about the potential for future flooding and drought.

An important takeaway is that the magnitude of variability overshadows the small projected decrease in average streamflow.[35] Changes in extreme events are likely to overwhelm average changes in both the eastern and western regions of the Northern Great Plains (Figure 22.2). Overall, climate models project an increase in the number of heavy precipitation events (events with greater than 1 inch per day) for much of the region, with the exception of the high-mountain areas in the southwestern portion. Societal risk increases any time natural conditions differ greatly from historical conditions,[43] with larger changes representing greater risks. Therefore, any large projected changes will require rethinking infrastructure design and operation. The probability for more very hot days (days with maximum temperatures above 90°F; Figure 22.2) is expected to increase, with potential impacts on agriculture, energy production, human health, streamflows, snowmelt, and fires. There are projected to be many fewer cool days (days with minimum temperatures less than 28°F, an indicator of damaging frost; Figure 22.2), with decreases of 30 days or more per year by mid-century. These changes would have important implications for the region's snowpack and consequently streamflow and water use.

Reservoir and groundwater storage are expected to be increasingly important as buffers against the impacts of increasing variability and to meet water demands during periods of shortage, especially in light of warming-driven losses in snowpack water and higher evapotranspiration rates, which reduce the total amount of water availability. It may be possible to move water between basins to alleviate flooding impacts, but this raises a new set of challenging hydrological and environmental issues. Future activities that increase water demand (population growth, expansion, or alteration of agriculture) will increase dependence on reservoir capacity and infrastructure integrity.

Key Message 2

Agriculture

Agriculture is an integral component of the economy, the history, and the culture of the Northern Great Plains. Recently, agriculture has benefited from longer growing seasons and other recent climatic changes. Some additional production and conservation benefits are expected in the next two to three decades as land managers employ innovative adaptation strategies, but rising temperatures and changes in extreme weather events are very likely to have negative impacts on parts of the region. Adaptation to extremes and to longer-term, persistent climate changes will likely require transformative changes in agricultural management, including regional shifts of agricultural practices and enterprises.

The Northern Great Plains region plays an important role in U.S. food security (see Tables 22.1 and 22.2), and agriculture has been integral to the history and development of the region. Agricultural uses in the region are diverse, including the largest remaining tracts of native rangeland in North America, substantial areas of both dryland and irrigated cropland and pasture, and mosaics of cropland and grazed

grassland and forested lands. This region is home to 7.2% of U.S. farms (152,663) but 23.8% of the U.S. land in farms, encompassing 218 million acres with 22.4% of the total cropland, 21.9% of irrigated lands, 29.3% of U.S. pasture and rangeland, and nearly one-third (30.1%) of lands in conservation/wetland reserve programs.[44] Livestock production (beef and dairy cattle and hogs) is dominant in the region. Important crops include corn, soybeans, wheat, barley, alfalfa, hay, and a diversity of other crops such as potatoes, sugar beets, dry beans, sunflowers, millet, canola, and barley (see Tables 22.1 and 22.2).[44] The Northern Great Plains region contributes 12.7% of the market value of agricultural products sold in the United States despite having only 1.5% of the U.S. population.

Extensive precipitation and temperature gradients and inherently high climatic variability, both within and between years, result in highly variable conditions for agricultural enterprises in the Northern Great Plains. The region receives the majority of its precipitation during the spring months (April, May, and June), with a high degree of year-to-year variability.[45] A mix of private, state, federal, tribal, and other land ownership across the region promotes heterogeneity at landscape-to-regional scales, which enhances the provision of numerous ecosystem goods and services, such as wildlife habitat, including for pollinators.

Percent of National Total Livestock Animals in the Northern Great Plains (2012)

	Beef cows	Hogs and pigs	Sheep and lambs	Milk cows	Egg layers
% of National Total	21.9%	6.9%	18.4%	2.0%	3.5%

Table 22.1: The table shows the percent of the national total of livestock animals living in the Northern Great Plains in 2012. Source: U.S. Agricultural Census 2012.[44]

Percent of National Total Crop Commodities in 2012

	Corn for grain (bu)	Corn for silage/ greenchop (tons)	Wheat for grain (bu)	Spring wheat (bu)	Durum wheat (bu)	Oats for grain (bu)
% of National Total	20.2%	11.5%	30.4%	70.6%	72.2%	20.3%

	Barley (bu)	Soybeans (bu)	Dry edible beans and lentils (cwt)	Forage (tons)	Sunflower seed (pounds)	Sugarbeets (tons)
% of National Total	48.4%	16.3%	48.6%	13.8%	83.6%	27.2%

Table 22.2: The table shows the percent of the national total production for crop commodities produced in the Northern Great Plains in 2012. Units are bushels (bu), tons, hundredweight (cwt), or pounds. Source: USDA National Agricultural Statistical Survey 2012.[44]

The Northern Great Plains is currently experiencing a marked transition in agricultural land use involving the conversion of grassland to annual crops[46,47] and an increased prevalence of monoculture cropping.[48] From peak enrollment in the Conservation Reserve Program (10 million acres in 2007), enrollment declined by half by 2017, with the majority of these lands returning to cropland (60%), thereby losing ecosystem service benefits such as wildlife habitat and improved water and soil quality.[49] Changing land use in the eastern part of this region is an outcome of trends of above-average precipitation over the last 10–20 years, with some of those precipitation trends having been driven by expansion of agricultural land use.[50] In the western part of the region, genetic developments in crop cultivars and varieties that enhance suitability of drier land for crop production have led to expansion of dryland cropping.

Despite a long history of high year-to-year variability,[45] producers are experiencing a changing climate and increasing weather variability and extreme conditions that are outside the ranges they have dealt with in the past.[51] Producers' daily and annual decision-making depends on market conditions for seeds and products, agronomic constraints, and climate change-related variables.[52] The decision-making process is challenged by a lack of experience with analogous climatic conditions in the past, thus increasing risks for land managers. This dependence on historical experience highlights the importance of the human element in the resilience of social–ecological systems, which have traditionally been viewed from the biophysical perspective.[53]

Temperature increases of 2°–4°F projected by 2050 for the Northern Great Plains under the lower scenario (RCP4.5) are expected to result in an increase in the occurrence of both drought and heat waves; these projected trends would be greater under the higher scenario (RCP8.5). The amount, distribution, and variability of annual precipitation in the Northern Great Plains are anticipated to change, with increases in winter and spring precipitation of 10%–30% by the end of this century and a decrease in the amount of precipitation falling as snow under a higher scenario (RCP8.5).[54] Summer precipitation is expected to vary across the Northern Great Plains, ranging from no change under a lower scenario (RCP4.5) to 10%–20% reductions under a higher scenario (RCP8.5).[54] Further, the frequency of heavy precipitation events is projected to increase, with an increase of about 50% in the frequency of two-day heavy rainfall events by 2050 under the higher scenario (RCP8.5). The amount falling in single-day heavy events is projected to increase 8%–10% by mid-century depending on scenario.[54] Although fewer hail days are expected, a 40% increase in damage potential from hail due to more frequent occurrence of larger hail is predicted for the spring months by mid-century under a higher scenario (RCP8.5).[55] Even with increases in precipitation, warmer temperatures are expected to increase evaporative demand, leading to more frequent and severe droughts.[56] Some of the negative effects of drying in a warmer climate are likely to be offset by elevated atmospheric carbon dioxide (CO_2) concentrations, which directly stimulate plant growth and increase plant water-use efficiency.[3]

The warmer and generally wetter conditions projected for some of the Northern Great Plains, coupled with elevated atmospheric CO_2 concentrations, are expected to

1. increase soil water availability during the primary growing season in the northern part of the region and decrease it the southern parts;[1,9]

2. increase the number of extreme temperature events (high daytime highs or nighttime lows) during critical pollination and grain fill periods, which will very likely reduce crop yields;[6,9]

3. lead to declining yield for crops[6] and forages[7,8] due to increasing temperatures, some of which will be offset by increasing CO_2;

4. increase the abundance and competitive ability of weeds and invasive species;[1,2]

5. alter plant phenology–for example, earlier onset of spring (Ch. 1: Overview, Figure 1.2j)[57] and earlier flowering of plants;[58]

6. decrease the quality of forage available to livestock;[3,59,60]

7. increase livestock production and efficiency of production due to greater net primary productivity and longer growing seasons;[3]

8. result in longer growing seasons at mid- and high latitudes;[4,5] and

9. increase the range and fecundity of crop pests.[9]

All of these changes will require increased flexibility in resource management.[61,62,63]

Adaptation for agricultural land use for the next 20–30 years, or to the mid-21st century, will be most effective when decision-making integrates biophysical, social, and economic components. Proactive learning opportunities that integrate experimental and experiential knowledge—such as lessons learned from early adopters—can help enhance decision-making. After all, many adaptations have already been implemented by a subset of producers in this region, providing opportunities for assessment, further development, and adoption. Context-specific decision-making for operations can also be improved through science–management partnerships, which aim to build adaptive capacity while being sensitive to multiple production, conservation, and environmental goals. Transfer of this adaptive knowledge in a timely manner to producers in the field through novel, multipronged communication efforts will assist land managers in more effectively and resiliently responding to the changes to come (see Case Study "Adaptive Rangeland Management"). The climate changes projected over the longer term (through the end of this century) are likely to require transformative changes in agricultural management, including regional shifts of agricultural practices and enterprises.[61,64]

Case Study: Adaptive Rangeland Management

Highly variable precipitation in the Northern Great Plains makes it difficult for managers to balance forage availability with animal demand. An emergent focus is on management strategies that are adaptive rather than prescriptive. But adaptive solutions require collaboration, often among stakeholders with different production and conservation goals. For example, grassbanking, in which ranchers lease land from property owners at a discount in exchange for carrying out conservation-related projects on their pastures, requires management strategies that can successfully deal with this variability. They can also require engagement between different land ownership types, including privately owned land, leased land, state lands, and federal lands. At The Nature Conservancy's Matador Ranch in north central Montana, local ranchers pay reduced grazing fees to graze their cattle on the Matador in exchange for wildlife-friendly and ecologically sound practices on their own operations, where a ranch management plan is required and sodbusting is prohibited. Each year, Conservancy staff and the ranchers develop a grazing plan for the Matador to reach production and ecologically based management goals, including the diverse vegetation structure needed by imperiled grassland birds and greater sage-grouse. In 2017, the Matador Grassbank ranches encompassed over 280,000 acres of private and public leased land. Working cooperatively, the Conservancy and grassbank members improved habitat for imperiled wildlife species on more than 340,000 acres, all while creating conditions that allow for sustainable ranch operations across variable and changing climatic conditions.

Learning how better decisions are made in the face of climate variability is a challenging research topic and one that also requires close collaboration—in this case between stakeholder groups and scientists. Another project, the Collaborative Adaptive Rangeland Management (CARM) experiment, which started in 2012 with a series of meetings involving ranchers, conservation/environmental organizations, and public land managers, is an example of such a research project. Conducted at a ranch-level scale for relevance to producers and managers, the research seeks to determine how adaptive rangeland management can be implemented in a manner that effectively responds to current and changing rangeland and weather/climatic conditions, incorporates active learning, and includes management decisions from a diverse stakeholder group based on quantitative, repeatable measurements collected at multiple spatial and temporal scales. An 11-person stakeholder group determined goals for vegetation, livestock, and wildlife. Specific objectives were developed for each, and testable hypotheses were derived for the scientists. The group also identified the need for baseline data and subsequent monitoring data to inform decisions made within the year, as well as from year to year. Following the implementation of more sustainable grazing management and prescribed fire treatments in 2014, interpretation of the monitoring data regarding progress towards accomplishing the desired objectives provided the opportunity for stakeholders and scientists to engage in shared learning and co-production of knowledge. CARM is a promising model for collaborative research that develops science-based management recommendations for multiple rangeland goals and objectives.

Key Message 3

Recreation and Tourism

Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are at risk in a changing climate. Rising temperatures have already resulted in shorter snow seasons, lower summer streamflows, and higher stream temperatures and have negatively affected high-elevation ecosystems and riparian areas, with important consequences for local economies that depend on winter or river-based recreational activities. Climate-induced land-use changes in agriculture can have cascading effects on closely entwined natural ecosystems, such as wetlands, and the diverse species and recreational amenities they support. Federal, tribal, state, and private organizations are undertaking preparedness and adaptation activities, such as scenario planning, transboundary collaboration, and development of market-based tools.

Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are ingrained in the region's cultures and at risk in a changing climate. Recreationists enjoyed roughly 13.1 million days of fishing in the region in 2011, along with 10.8 million days of hunting and 8.7 million days of wildlife-watching. The region contains two dozen national parks, monuments, and historic sites. This subset of outdoor recreationists alone—among a wider population who pursue additional outdoor recreation activities in the region—spent over $4.9 billion on these activities during 2011 ($5.2 billion in 2015 dollars).[65,66,67,68,69]

Climate change affects recreation through three pathways: 1) direct impacts to the ecosystems and wildlife or fish populations of interest (for example, increasing water temperature impacting coldwater fish survival); 2) changes in environmental conditions that directly affect recreationists (for example, increased water temperatures resulting in brief river closures for angling to minimize additional stress on sensitive fish species); and 3) effects of adaptation policies on habitat quality or recreational enjoyment (for example, energy policies that result in higher fuel costs, making distant trips more expensive).[70] These three pathways have not been fully quantified for most recreational systems, within or beyond the Northern Great Plains, and the third pathway is only speculative—it has not yet been documented in the scientific literature. Scientific understanding is most complete for the first pathway—the extent and ways in which climate change affects ecosystems that support outdoor recreation.[70]

Climate-related impacts are already being felt in the region's terrestrial and aquatic ecosystems, as well as the local economies that depend upon them. Climate-driven changes in snowpack, spring snowmelt, and runoff have resulted in more rapid melting of winter snowpack and earlier peak runoff due to rapid springtime warming.[71,72,73] These effects have resulted in lower streamflows, especially in late summer.[74] Lower flows, combined with warmer air temperatures, have caused stream temperatures to rise.[75,76,77] These conditions are negatively affecting aquatic biodiversity (e.g., Hotaling et al. 2017[78]) and ecosystem functions of riparian areas (areas along the banks of rivers and streams; e.g., Tonkin et al. 2018[79]), with important consequences for local economies that depend upon river-based recreation. For example, higher stream temperatures are accelerating the hybridization and genetic dilution of native trout species

with nonnative trout species.[80] Similarly, shifts in habitat suitability in favor of warmwater fish species are projected to reduce the value of coldwater fishing in the Northern Great Plains by $25 million per year under RCP4.5 by the end of the century and by $66 million per year under RCP8.5 (in 2015 dollars).[81] Higher stream temperatures are already increasing the vulnerability of coldwater fish species to diseases, such as proliferative kidney disease (PKD).[82,83,84] PKD killed thousands of native mountain whitefish in Montana during 2016, which triggered a month-long closure of 180 miles of the Yellowstone River to all water-based recreation.[85] Economic impacts to local communities are still being quantified, but initial estimates range from $360,000 to $524,000 (in 2014 dollars; range is from $363,600 to $529,240 in 2015 dollars).[86]

In the mountainous areas of the region, climate change is impacting snow-dependent ecosystems and economies. In Wyoming and Montana, for example, higher-than-normal winter and fall temperatures and low summer precipitation are enabling severe mountain pine beetle outbreaks in whitebark pine.[87] Whitebark pine is a keystone species of high-elevation ecosystems, providing a critical seed source for more than 20 wildlife species, creating microenvironments that allow other tree species to establish, and influencing snowpack dynamics.[88,89] Whitebark pine is also an important cultural resource for some tribes in the region.[90]

In the future, warmer temperatures and changes in precipitation are expected to decrease the extent and duration of snow cover across much of the northern hemisphere. In the mountains of western Wyoming and western Montana, the fraction of total water in precipitation that falls as snow (from October 1 to March 31) is expected to decline by 25% to 40% by 2100 under a lower scenario (RCP4.5).[10] The last day of the snow season is also expected to arrive earlier in the spring. Under a lower scenario (RCP4.5), it is expected to occur roughly 20 days sooner by 2050 and 30 days sooner by 2100. Under a higher scenario (RCP8.5), it is expected to occur 80 days sooner by 2100.[10] This would negatively affect the region's winter recreation industry, including snowmobiling, cross-country skiing, and downhill skiing.[11]

Under a lower scenario (RCP4.5), the season length for cross-country skiing and snowmobiling in northwestern Wyoming and western Montana is expected to decline by 20% to 60% by 2090.[11] Under the higher scenario (RCP8.5), the projected decline is more severe: 60% to 100%.[11] Similar losses in season length are projected for the region's downhill skiing industry—a $275 million industry.[11] The number of visitors to downhill ski areas is, therefore, expected to decline. Under RCP4.5, visitors are projected to decline by 13% by 2050 and 22% by 2090 (holding population constant); under RCP8.5, projected declines are 19% by 2050 and 49% by 2090.[11] Similar declines are projected for the region's $4.6 million cross-country ski industry and $2.3 million snowmobiling industry (in 2015 dollars).[11] Such reductions in visitor numbers would cause ripple effects across the local economies of snow-dependent communities.

At lower-elevation areas of the Northern Great Plains, natural ecosystems are often embedded within agricultural landscapes. Climate-induced land-use changes in agriculture can, therefore, have cascading effects on closely entwined natural ecosystems, such as wetlands,[12] and the diverse species and recreational opportunities they support. Technological and economic forces within agriculture are also driving land-use changes, which accelerate the degradation of wetlands. For example, in South Dakota and North Dakota, changing climatic and market conditions have enabled

agriculture shifts from pasture to small grains, or small grains to corn and soybeans.[12] Nearly 40% of these land-use changes have occurred within 300 feet of neighboring wetlands, reducing the quantity of wetlands and the quality of their ecological functions (see Case Study "Wetlands and the Birds of the Prairie Pothole Region").[46] For example, conversion of pasture to cropland or of winter-seeded crops to spring-seeded crops reduces waterfowl nest survival by increasing habitat fragmentation, which makes nests more vulnerable to predation.[91,92] Tillage in newly converted fields also increases the risk of soil being washed into nearby wetlands, reducing their biological productivity and floodwater storage capacity.[93] These changes have cascading effects not only on wetland-dependent waterfowl but also on shorebirds, fish, amphibians, aquatic insects, and plants. Waterfowl hunting and watching are important cultural and economic activities in rural communities of the Northern Great Plains.[94] In South Dakota alone, hunters spent $84.7 million in 2015–2016 on migratory bird hunting (in 2016 dollars; $83.9 in 2015 dollars).[95]

Higher temperatures, reduced snow cover, and more variable precipitation would make it increasingly challenging to manage the region's valuable wetlands, rivers, and snow-dependent ecosystems to sustain today's levels of natural amenities and associated recreational opportunities. Federal, tribal, state, and private organizations are undertaking preparedness and adaptation activities, including scenario planning, to discuss current climate-driven challenges and envision future challenges and responses. The North Central Climate Adaptation Science Center, for example, has facilitated scenario planning exercises for southwestern South Dakota in the vicinity of Badlands National Park and for central North Dakota in the vicinity of Knife River Indian Villages National Historic Site.[96] The Crown Adaptation Partnership—a transboundary team of scientists and resource managers from the United States, Canada, and Tribes/First Nations—is collaborating on climate change adaptation strategies across multiple jurisdictions to enhance resilience of the Crown of the Continent Ecosystem in northern Montana, southwestern Alberta, and southeastern British Columbia.[97] Finally, private organizations have been partnering with researchers to develop "payments-for-ecosystem services," an emerging tool to address land-use change on private agricultural acreage.[98] This market-based tool, when designed appropriately, can encourage private landowners to provide wetlands, wildlife habitat, pollinator habitat, and other valued ecosystem services rather than converting land to uses that produce fewer ecosystem services.[99,100]

Photo taken along the White River in Badlands National Park, South Dakota in September 2016. Photo credit: Christian Collins (CC BY-SA 2.0).

The region's valued ecosystems and recreational opportunities are being affected by climate change to an extent not fully understood, but increasingly being studied. Existing knowledge is primarily based on local and regional case studies, often about specific recreational activities or individual wildlife species. This makes comprehensive assessment a challenge and highlights the need for additional work to fill remaining gaps.[101]

Case Study: Wetlands and the Birds of the Prairie Pothole Region

The North American Prairie Pothole Region (PPR) is a globally important natural resource, a portion of which covers northern and eastern North Dakota, eastern South Dakota, and far northern Montana. The PPR hosts nearly 120 species of wetland-dependent birds representing 21 families[102] and provides prime nesting and migratory habitat for waterbirds, including ducks and shorebirds.[103,104] Estimates suggest that 50% to 75% of all North American waterfowl hatch in the PPR.[105]

Aerial view of the Prairie Pothole Region in South Dakota. Photo credit: © Patrick Ziegler/iStock/GettyImages.

Climate change is affecting wetlands and the bird species they support in the Northern Great Plains, both directly and indirectly. Changes in spring precipitation affect wetlands directly because spring snowmelt, runoff, and refill influence wetland hydrology (including the number of days with standing water and water depth) and plant cover.[106] A warmer climate, if not offset by enough additional precipitation, will shrink wetland areas in the PPR and reduce waterfowl and shorebird habitat. To offset a temperature increase of 5.4°F (3°C), precipitation would need to increase by 20% or more.[106] If a 5.4°F (3°C) increase in average annual temperature occurs and is only offset by a 10% increase in average annual precipitation, much of the wetland habitat in the PPR will be lost.[107,108] Densities of wetlands are predicted to decline on average by 20% to 25% by mid-century under a higher scenario (RCP8.5).[109] In a warmer and drier climate, much of the PPR will be too dry to support historical levels of waterfowl nesting and production,[106] with one study projecting that 28 of 29 species studied will lose range in the future under the higher scenario (RCP8.5).[102]

Wetland and bird losses due to climate change are exacerbated by agricultural land-use change in the PPR, with grasslands and pastures being converted to wheat, corn, and soybeans.[12,46] The degradation of wetland function due to land-use change (Figure 22.4) is driven in part by the increasing profitability of row crops under higher temperatures and increased precipitation in the eastern Dakotas.[12] Land-use change in agriculture to less wetland-friendly crops is also driven by policy and market forces tied indirectly to climate. The ethanol industry's rise in the mid-2000s, for example, contributed to increases in corn prices.[110] Rising prices triggered a northwestward expansion of the historical Western Corn Belt into the PPR, and into close proximity to wetlands.[46] As a result, grassland nesting bird populations are declining faster than any other group of birds in North America.[111,112] Grassland conversion rates such as these (Table 22.3) have not been seen in the Corn Belt since the rapid mechanization of U.S. agriculture in the 1920s and 1930s.[113]

Case Study: Wetlands and the Birds of the Prairie Pothole Region, *continued*

Land-Cover and Land-Use Changes for the Prairie Pothole Region

	Changes in Area (thousands of acres)		
State	**Grassland to Corn/Soy**	**Corn/Soy to Grassland**	**Grassland Net Loss**
Nebraska	309	247	62
North Dakota	320	100	220
South Dakota	632	181	451
Montana	n/a	n/a	n/a
Total	**1,261**	**528**	**733**

Table 22.3: This table shows changes in land cover and land use in the Northern Great Plains portion of the Prairie Pothole Region (PPR), by state, from 2006 to 2011. Note: Montana was not included in the analysis of changes in the PPR cited here, so comparable statistics are not available. Map-based estimates of grassland conversion in Montana from 2008–2012, though not specifically for the PPR, are available from other studies.[47,114] Source: adapted from Wright and Wimberly 2013.[46]

Reductions in Grassland Area in the Prairie Pothole Region

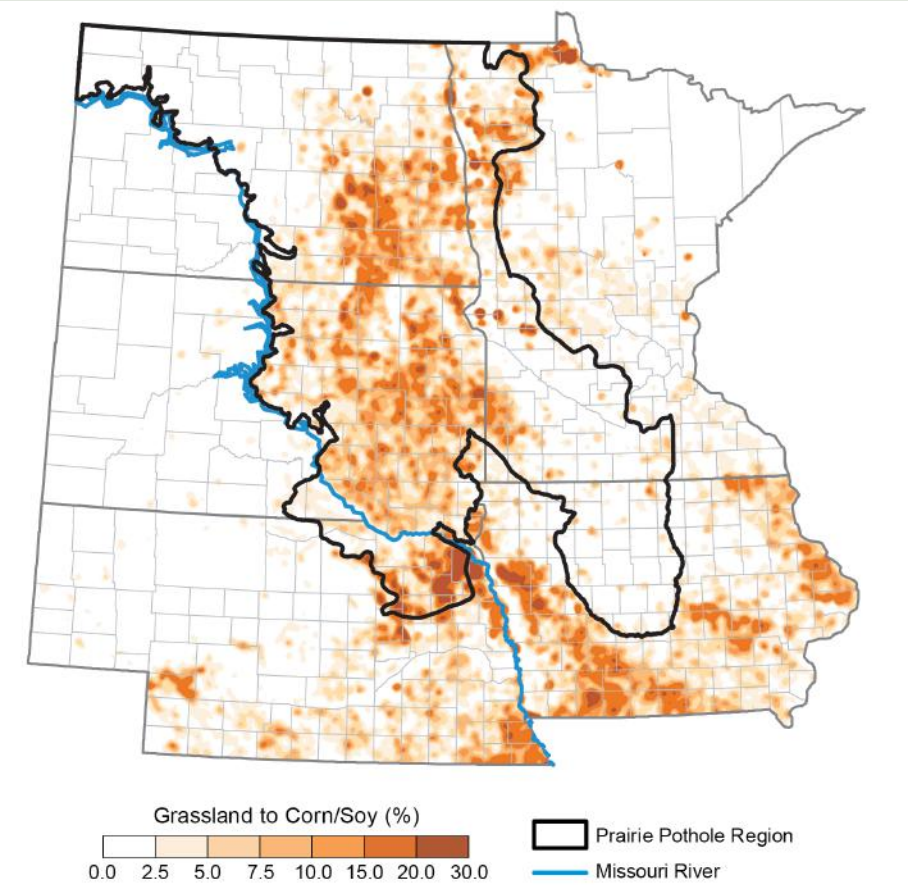


Figure 22.4: The figure shows the loss of grassland to corn/soy between 2006 and 2011 in the eastern states of the Northern Great Plains (Nebraska, South Dakota, and North Dakota), expressed as a percentage of 2006 grassland acres. Outlined in black is the boundary of the U.S. portion of the Prairie Pothole Region, a substantial portion of which was converted from grassland to corn/soy between 2006 and 2011. Source: adapted from Wright and Wimberly 2013.[46]

Key Message 4

Energy

Fossil fuel and renewable energy production and distribution infrastructure is expanding within the Northern Great Plains. Climate change and extreme weather events put this infrastructure at risk, as well as the supply of energy it contributes to support individuals, communities, and the U.S. economy as a whole. The energy sector is also a significant source of greenhouse gases and volatile organic compounds that contribute to climate change and ground-level ozone pollution.

Energy resources in the Northern Great Plains include abundant crude oil, natural gas, coal, wind, stored water, and, to a lesser extent, corn-based ethanol, solar energy, and uranium. The infrastructure associated with the extraction, distribution, and energy produced from these resources is vulnerable to the impacts of climate change, including increasing average temperatures and heat waves, decreasing water availability in the summer, and an increase in the frequency and severity of heavy precipitation events leading to floods.[13]

Energy infrastructure vulnerabilities relate to how fuel is transported and how energy is produced, generated, transmitted, and used. For example, railroads and pipelines are vulnerable to damage or disruption from increasing heavy precipitation events and associated flooding and erosion.[13] Summer heat waves also damage railroad tracks and are expected to reduce thermoelectric power plant and transmission line capacity,[13] though estimates of the likelihood, timeframe, or magnitude of such impacts are limited. Higher temperatures are likely to lower the yields of crops used for biofuels while shifting northward the range in which certain biofuel crops (such as corn) can be cultivated.[13] Biorefineries are vulnerable to decreasing water availability during drier summers and periods of drought.[13] Declining water availability in the summer would likely increase costs for oil production operations, which require freshwater resources.[13] These cost increases will lead either to reduced production or be passed on to consumers. Finally, higher maximum temperatures, longer and more severe heat waves, and higher overnight lows are expected to increase electricity demand for cooling in the summer, further stressing the power grid.[13] Increasing demands for electricity in response to increasing temperatures are projected to increase costs to the power system by approximately $13–$18 million per year by 2050 under the higher scenario (RCP8.5) and $42–$80 million per year by 2090 under the same scenario (in 2015 dollars).[81]

These risks to the energy sector are likely to negatively impact individuals, communities, and the economy, and are also likely to require new planning and preparedness options for the short and long term. While such efforts have already begun, more widespread and coordinated strategies would help maximize risk reduction to the energy sector.

Examples of energy sector resilience solutions include actions like railroad preventive maintenance, upgrades, and reliability standards; water-efficient cooling technologies for thermoelectric power plants, such as recirculating or wet–dry hybrid systems; and programs that reduce total and peak electricity demand.[13] Such programs, often run by electric utilities, use rebates and cash incentives to encourage customers to purchase more efficient appliances and equipment like lighting, pumps, water heaters, and air conditioners.

The energy sector is also a significant source of greenhouse gas emissions in the Northern Great Plains, as illustrated in Figure 22.6.[81] Methane is released during the production, processing,

transmission, storage, and distribution of natural gas. CO_2 and methane are released during the production, transportation, and refining of petroleum. Coal mining also releases methane. CO_2 is emitted from the combustion of coal and natural gas to produce electricity and from the combustion of petroleum for transportation.[117] Natural gas and petroleum systems also emit volatile organic compounds, or VOCs, that contribute to the formation of ground-level ozone pollution. Climate change is generally expected to increase such ozone pollution in the future throughout much of the United States, in part due to higher temperatures and more frequent stagnant air conditions (Ch. 13: Air Quality). Unless offset by additional emissions reductions of ozone precursors, these climate-driven increases in ozone are forecast to cause premature deaths, hospital visits, lost school days, and acute respiratory symptoms.[118]

Floodwaters Surround Nuclear Power Plant in Nebraska

Figure 22.5: Floodwaters from the Missouri River surround the Omaha Public Power District's Fort Calhoun Station, a nuclear power plant just north of Omaha, Nebraska, on June 20, 2011. The flooding was the result of runoff from near-record snowfall totals and record-setting rains in late May and early June (NWS 2012).[115] A protective berm holding back the floodwaters from the plant failed, which prompted plant operators to transfer offsite power to onsite emergency diesel generators. Cooling for the reactor temporarily shut down, but spent fuel pools were unaffected.[116] Photo credit: Harry Weddington, U.S. Army Corps of Engineers.

Greenhouse Gas Emissions from Fuel Production

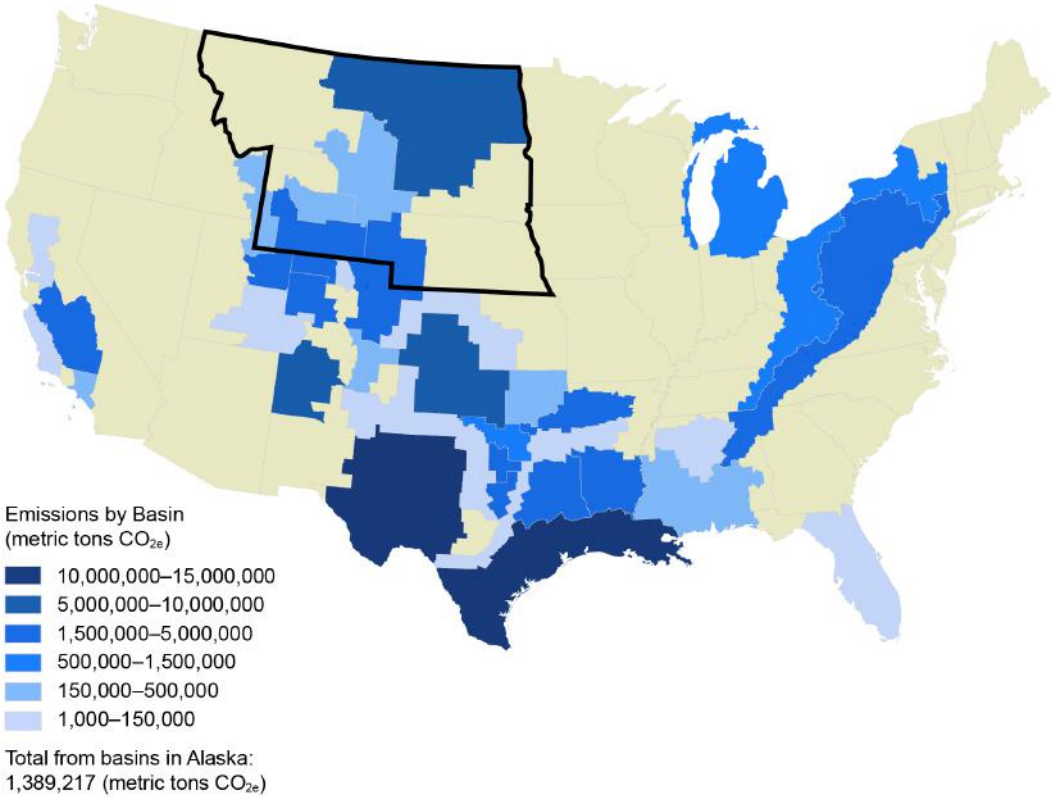


Figure 22.6: Greenhouse gas emissions (shown here in metric tons of carbon dioxide equivalent, or CO_{2e}, per geologic basin) from petroleum and natural gas production facilities in the Northern Great Plains are among the highest in the United States. The data used to produce this map are from EPA's Greenhouse Gas Reporting Program, which only includes facilities that emit 25,000 metric tons of CO_{2e} or more annually.[117] Each production facility must provide the total emissions from all their well pads in a geologic basin. Source: adapted from EPA 2017.[117]

Strategies being employed in the region to reduce greenhouse gas emissions from the energy sector include increasing the performance of coal-fired power plants; offsetting fossil fuel-fired generation with renewable energy; conducting methane leak detection and repair programs using remote sensing technologies at natural gas operations; upgrading the equipment used to produce, store, and transport oil and gas; and demand-side management of electricity use.

Key Message 5

Indigenous Peoples

Indigenous peoples of the Northern Great Plains are at high risk from a variety of climate change impacts, especially those resulting from hydrological changes, including changes in snowpack, seasonality and timing of precipitation events, and extreme flooding and droughts as well as melting glaciers and reduction in streamflows. These changes are already resulting in harmful impacts to tribal economies, livelihoods, and sacred waters and plants used for ceremonies, medicine, and subsistence. At the same time, many tribes have been very proactive in adaptation and strategic climate change planning.

The rich cultural heritage of the Northern Great Plains began with the region's Indigenous peoples who are now in 27 federally recognized tribes, 1 state-recognized tribe in Montana, and several unrecognized tribes in addition to the myriad Native Americans spread throughout the towns, cities, and rural areas of the region (Figure 22.7). Because tribes and Indigenous peoples are among those in the region with the highest rates of poverty and unemployment, and because many are still directly reliant on natural resources, they are among the most at risk to climate change.[24,25,27,28,29,30,31]

Indigenous peoples in the region are observing many climate and seasonality changes to their natural environment and ecosystems, many of which are impacting livelihoods as well as traditional subsistence and wild foods, wildlife, plants and water for ceremonies and medicines, and health and well-being (see Case Study "Crow Nation and the Spread of Invasive Species").[14,15,16,17,18,19,20,21,22,23,24,25,26] Specifically, tribal elders and natural resource managers in the region have observed seasonal changes, such as those in hydrological cycles, phenology, bird migrations, and bear hibernation cycles, as well as reduced availability of traditional plant-based foods and the decline in pine tree species. There is also a mismatch between traditional stories and current climate and seasons.[14,19] They are also experiencing significant impacts to subsistence fisheries and riparian ecosystem health, including declines in salmon, trout, frogs, and mussels as a result of reduced streamflow and warmer water temperatures.[19,26,119,120] Extreme heat and declines in traditional plants (such as sage, cottonwoods, and cattails) are already impacting summer outdoor ceremonies when participants fast and camp for days.[19] In addition, tribes are experiencing increased fire frequency and intensity, and climate projections that show increased fire risks for the region are causing concern for the health of forests, wildlife, freshwater systems and fisheries, and human health.[14,19]

Northern Great Plains Tribal Lands

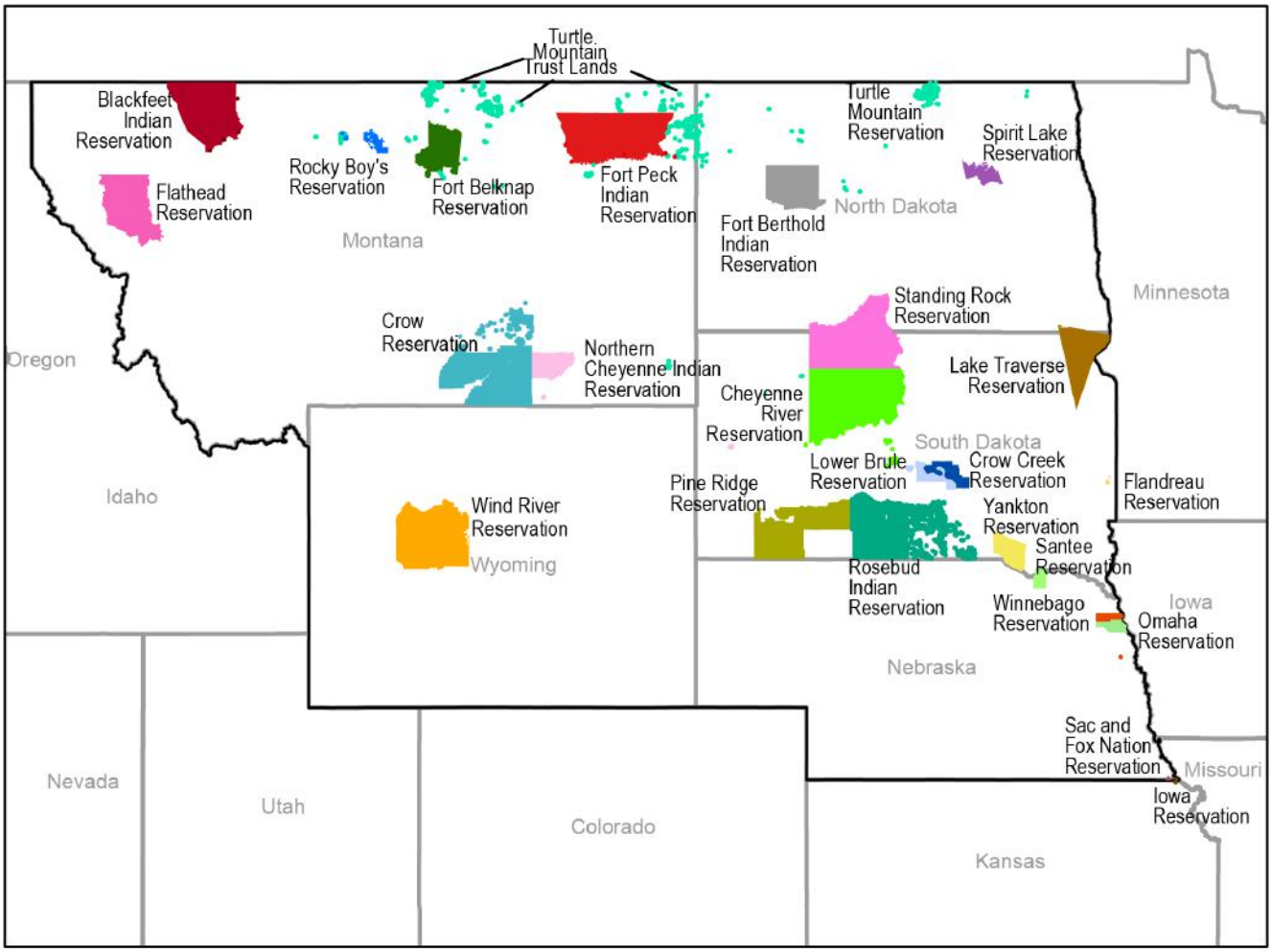


Figure 22.7: The map outlines reservation and off-reservation tribal lands in the Northern Great Plains, which shows where the 27 federally recognized tribes have a significant portion of lands throughout the region. Information on Indigenous peoples' climate projects within the Northern Great Plains is described in Chapter 15: Tribes and Indigenous Peoples. Sources: created by North Central Climate Science Center (2017) with data from the Bureau of Indian Affairs, Colorado State University, and USGS National Map.

To the Indigenous peoples of the Northern Great Plains, the Lakota phrase Mni wiconi means "water is life." Water plays significant cultural, religious, and economic roles across tribal communities that transcend consumptive water use. Because water is so integral, these communities are particularly sensitive to climate change impacts on water in the form of extreme flooding and droughts, changes in snowpack, and changes in the timing of precipitation events. These climate sensitivities, along with substandard water infrastructure and complex institutions and water rights, all combine to create water insecurity.[14,18,19,20,23,24,28,120,121,122,123,124] In the Northern Great Plains, just under 29,000 (76%) Indigenous households are in need of new or improved sanitation facilities, and approximately 5,000 households lack safe water supply, sewage facilities, or both.[125] The total cost to remediate sanitation facility deficiencies in the region was estimated at around $280 million according to a 2015 annual report from the Indian Health Service.[125] Climate change has already begun to exacerbate the problem of disruptions to water supplies from decreased water availability, as happened in 2003 when Standing Rock Reservation ran completely out of water during drought.[28]

Case Study: Crow Nation and the Spread of Invasive Species

A warming climate is projected to hasten the spread of invasive species within riparian ecosystems.[134,137,138,139] Indigenous populations who harvest and hold sacred flora and fauna along rivers within the semiarid region of south central Montana are particularly vulnerable.[140] Post-reservation settlement of Treaty Tribes and multiple land policies aimed at assimilation of Native American Tribes in the United States created a checkerboard of land ownership within reservation boundaries. The Apsaalooké, or Crow, Reservation was established after the Fort Laramie Treaty of 1886 and is located within the mountains and valleys along the Little Bighorn and Bighorn Rivers in south central Montana.[141] Promotion of agriculture in the late 19th century, along with the establishment of divergent dams for floodplain irrigation, resulted in decreased water flows, affecting the natural pulse of these river systems and their associated native riparian species. Cascading effects of river regulation, along with intentional planting of the invasive species Russian olive (*Elaeagnus angustifolia* L.) during the Indian Emergency Conservation Work era of the 1930s, have drastically altered natural vegetation within these watersheds (Figure 22.8). These complex networks of policy and culture determine the ways in which land and riparian regimes were drastically changed. The resulting conditions favored invasive plants and ecosystem degradation.[142]

The Apsaalooké, or Crow, people regularly harvest riparian plant species for food, ritual, and ceremonial uses. For example, plains cottonwood (*Populus deltoides*, Marsh) and willow (*Salix sp.* L.) are used for ceremonial (sweat lodge and Sun Dance) purposes. Crow Elders indicated that they must travel on average more than 15 miles farther now than they did 25 years ago to locate cottonwoods of specific sizes. They also find it difficult to locate and harvest traditional food sources such as chokecherry (*Prunus americana* L.) and buffalo berry (*Shepherdia argentea* Pursh., Nutt.). What was once a cottonwood- and willow-dominated river system is now dominated by Russian olive. Populations of salt cedar are likewise increasing along both the Bighorn and Little Bighorn Rivers and associated floodplains. Projections using habitat species distribution models suggest that Russian olive plants will continue to spread in the next 10 years as a result of increasing temperatures and precipitation (Figure 22.8). Continued spread of Russian olive species ultimately threatens the ability of the Crow people to harvest culturally important riparian species that provide subsistence, medicine, and plant species used in ceremony.[140]

The Russian olive invasion is a challenge throughout the Northern Great Plains. Here, the trees grow on ranchland on the Crow Indian Reservation. Photo credit: Kurrie Jo Small.

Case Study: Crow Nation and the Spread of Invasive Species, *continued*

Projected Expansion of Russian Olive Habitat

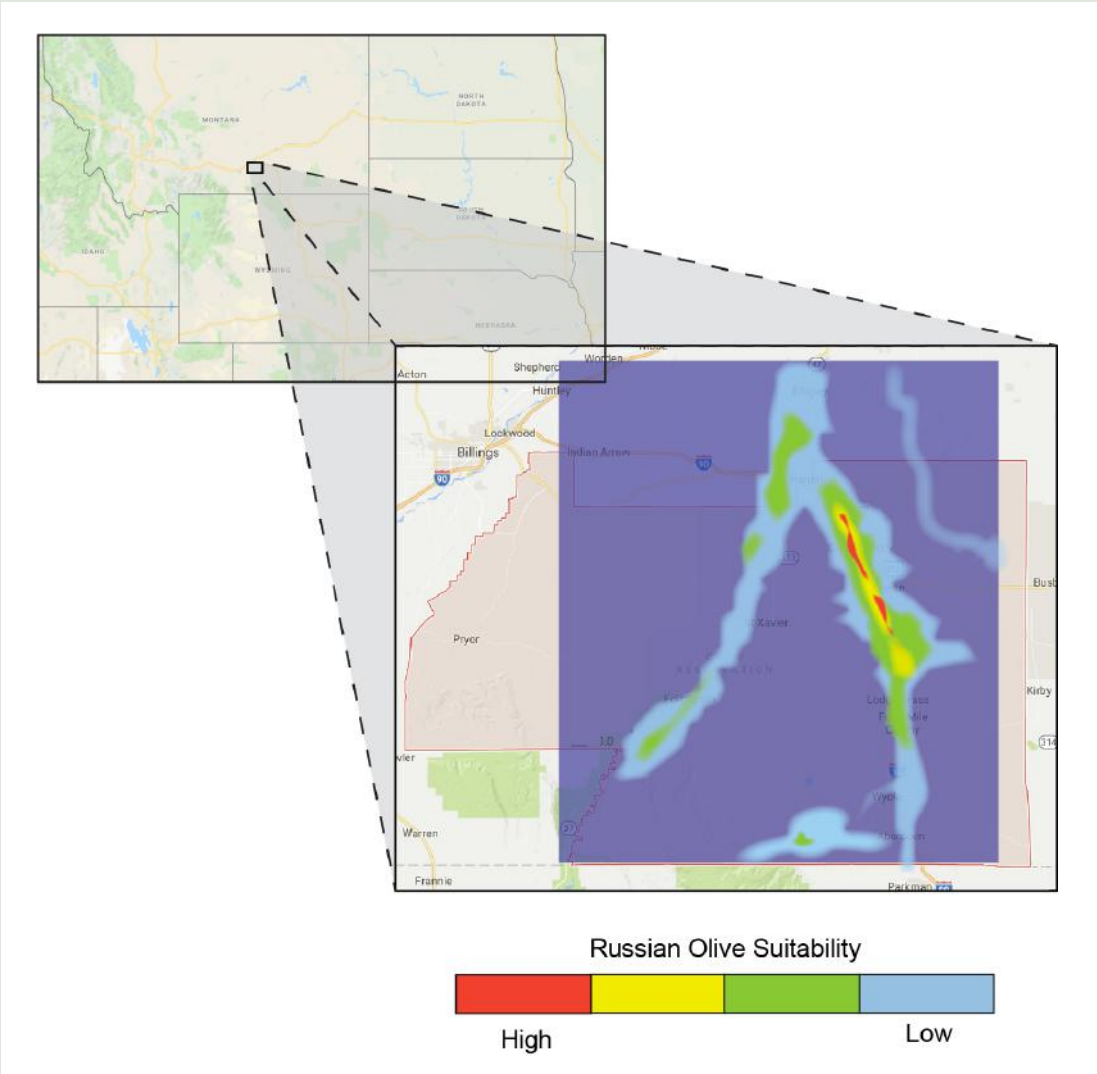


Figure 22.8: The map shows the projected expansion by 2021 of Russian olive habitat. Warmer colors indicate favorable habitat for future spread of Russian olive based on mapped presence points along the Little Bighorn and Bighorn Rivers within the Crow Indian Reservation in south central Montana. The Crow Reservation is outlined and shaded in red. Purple areas are outside of the suitability zone. Source: University of Arizona. Map data © 2018 Google, INEGI.

Reservation Irrigation Projects: Deferred Maintenance and Replacement Costs

Irrigation Project	Deferred Maintenance for FY 2014	Replacement Value
Blackfeet	$26,000,000	$50,000,000
Flathead	$82,000,000	$237,000,000
Fort Belknap	$8,000,000	$19,000,000
Fort Peck	$13,000,000	$33,000,000
Crow	$17,000,000	$59,000,000
Wind River	$30,000,000	$93,000,000
Total	**$176,000,000**	**$491,000,000**

Table 22.4: This table shows deferred maintenance and replacement costs for U.S. Bureau of Indian Affairs irrigation projects on six Northern Great Plains reservations (in 2014 dollars). Source: U.S. Government Accountability Office 2015.[126]

Agriculture, particularly livestock ranching, is a primary tribal livelihood in the region, and warmer temperatures and changes to water cycles (for example, reduced snowpack, earlier transition from snow to rain, and reduced or early runoff) pose a large threat and are already drying soils, reducing forage production, increasing livestock stress, and reducing water availability for irrigation systems throughout the region.[20,120] Reservations in the region would require a combined $176 million in maintenance or $491 million to replace neglected and failing Bureau of Indian Affairs irrigation systems (Table 22.4).[126] High leakages and inefficiencies in these systems hinder effective management of water and irrigation systems for climate change.[20]

Tribes have unique water rights and layers of relevant state and federal laws (for example, the Winters Doctrine and state water rights adjudication, and Prior Appropriation laws in the West). Climate change impacts on water resources are very likely to be compounded by these legal complexities, especially in cases where state water laws supersede tribal water codes and water rights during times of scarcity, such as at Wind River Reservation, where the Wyoming Supreme Court ruled that the state has primary authority.[20,123,127,128] Indigenous people in the region are also very concerned about the consequences of major oil pipelines passing through the region. Their concerns are in part focused around potential leaks, which would impact water resources already stressed by climate change. This concern is further intensified by the reality that climate change is projected to damage infrastructure in the region, including pipelines, through extreme storm or precipitation events that cause flooding.[54,56,121]

Disaster management is another area of great concern for the Northern Great Plains tribes. Over the last two decades, tribes have experienced unusually catastrophic fires, floods, and droughts that are already straining response capacities,[25] and climate change is expected to increase the need for the ability to fight fires, floods, and droughts.[14,16,25,129,130,131] Severe droughts in this century have resulted in serious impacts, such as tribal ranchers liquidating herds and reservations possessing no water at all.[28] Extreme hydrological events on the region's reservations are also happening in quick succession, such as the 2011 floods followed by severe drought and fire in 2012.[19,20,25,28] Each event strains the response capacity, and for the many tribes struggling with a lack of disaster preparedness, successive events compound the challenge.[25,28] This has widespread impacts on tribal economies and

livelihoods, domestic and municipal water supplies, and health and well-being.

Many climate adaptations are underway in Northern Great Plains Indigenous communities, but tribes also face unique legal and regulatory barriers because of post-colonial resettlement and reservation impacts of land fragmentation and uneven regulation by federal agencies. For example, the trust relationship with the Federal Government, where the Federal Government holds the titles of tribal lands "in trust" for the tribes, requires federal permission for many aspects of land and resource management.[14,15,16,17,18,20,25,131,132,133,134,135] Outside of these limitations, however, the tribes do have control over the reservations' built environment and housing. For example, the Oglala Lakota Nation (Pine Ridge) in South Dakota has created a sustainability plan that includes off-grid, climate-resilient housing and sustainable agriculture.[16,17,122,136] Other climate adaptation examples include Flathead Reservation's strategic climate planning for multiple sectors and species of cultural and economic importance; several South Dakota tribes' climate vulnerability assessment and drought planning; Wind River Reservation's drought assessment and preparedness; Northern Cheyenne Tribe's Integrated Resource Management Planning that will include climate change; and Fort Belknap's climate adaptation plan, which integrated planning with fire, forestry, and invasives management.[14,20,25] The InterTribal Buffalo Council also has drought and climate adaptation grants to prepare tribal bison herd managers in the region and beyond for climate impacts to bison pastures and water sources. There are multiple tribal initiatives that focus on climate and Indigenous knowledge-based education, outreach, and information sharing between tribes. For example, the Northern Cheyenne Indigenous land-based science learning program offers apprenticeships for youth interested in bio-cultural restoration science. The program, which sits in the tribe's Department of Environmental Protection and Natural Resources, aims to increase tribal knowledge around Indigenous and western sciences and thus enable youth to reclaim their responsibility to the land. Also, the Blackfeet and Confederated Salish and Kootenai Tribes collaborated on a regional workshop with First Nations throughout the region to share ideas and strategies and provide support for tribal climate adaptation planning.[25] Tribes are increasingly drawing on their deep, place-based connections to natural cycles and Indigenous knowledge, combined with western technical sciences, to respond to and prepare for climate change.[14,15,16]

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Traceable Accounts

Process Description

The chapter lead (CL) and coordinating lead author (CLA) developed a list of potential contributing authors by soliciting suggestions from the past National Climate Assessment (NCA) author team, colleagues and collaborators throughout the region, and contributors to other regional reports. Our initial list of potential authors also included CL nominees submitted to the U.S. Global Change Research Program (USGCRP). The CL and CLA discussed the Northern Great Plains, which was part of the larger Great Plains region for the Third National Climate Assessment (NCA3), with each of these nominees and, as part of that discussion, solicited suggestions for other nominees. This long list of potential contributing authors was pared down by omitting individuals who could not contribute in a timely fashion, and the list was finalized after reconciliation against key themes within the region identified by past NCA authors, the CL and CLA, and contributing author nominees. The team of contributing authors was selected to represent the region geographically and thematically, but participants from some states who had agreed to contribute were eventually unable to do so. Others were unable to contribute from the start. The author team is mostly composed of authors who did not contribute to NCA3.

The CL and CLA, in consultation with past NCA authors and contributing author nominees, identified an initial list of focal areas of regional importance. The author team then solicited input from colleagues and regional experts (identified based on their deep ties to scientific and practitioner communities across the region) on their thoughts on focal areas. This list informed the agenda of a region-wide meeting held on February 22, 2017, with core locations in Fort Collins, Colorado, and Rapid City, South Dakota. The main purpose of this meeting was to seek feedback on the proposed list of focal areas. With this feedback, the author team was able to refine our focal areas to the five themes comprising the Key Messages of the Northern Great Plains regional chapter. Of these, recreation/tourism is a focus area that is new from NCA3.

Key Message 1

Water

Water is the lifeblood of the Northern Great Plains, and effective water management is critical to the region's people, crops and livestock, ecosystems, and energy industry. Even small changes in annual precipitation can have large effects downstream (*very high confidence*); when coupled with the variability from extreme events, these changes make managing these resources a challenge (*very high confidence*). Future changes in precipitation patterns, warmer temperatures, and the potential for more extreme rainfall events are very likely to exacerbate these challenges (*very likely, high confidence*).

Description of evidence base

Multiple lines of research have shown that as a result of its high aridity, changes in water availability in the Northern Great Plains region are highly sensitive to small changes in climate.[35,36,143,144] Despite large differences in climate from the western mountains to the eastern plains, the reliance

upon reservoir storage to regulate water supplies is ubiquitous—to provide water during times of drought and to mitigate flood waters during deluges.

Natural reservoirs, groundwater, and snowpack are at risk to varying degrees. Reservoir vulnerability was recently analyzed to assess sustainable pumping rates,[42] while snow and especially glaciers appear to be in steady decline in recent decades,[38] attributed to global climate warming[39] that is projected to continue.[145]

Major uncertainties

While there is high confidence in future increases in temperature, uncertainties exist as to the changes in precipitation and runoff. Perhaps most important are the uncertainties in the degree of precipitation variability from year to year and within season (based on information dating to the 1950s).[35,52] These uncertainties are very likely to overwhelm the projected modest increases in precipitation.

Uncertainties exist in agricultural demands for water, reservoir operation protocols, and changes in extreme events.

Description of confidence and likelihood

There is *high confidence* that temperatures will rise in the region, which will *likely* produce less snowfall and smaller mountain snowpacks. There is *very high confidence* in the downstream consequences of these changes.

Key Message 2

Agriculture

Agriculture is an integral component of the economy, the history, and the culture of the Northern Great Plains. Recently, agriculture has benefited from longer growing seasons and other recent climatic changes (*very high confidence*). Some additional production and conservation benefits are expected in the next two to three decades as land managers employ innovative adaptation strategies (*very likely, high confidence*), but rising temperatures and changes in extreme weather events are very likely to have negative impacts on parts of the region (*very likely, very high confidence*). Adaptation to extremes and to longer-term, persistent climate changes will likely require transformative changes in agricultural management, including regional shifts of agricultural practices and enterprises (*very likely, high confidence*).

Description of evidence base

Several lines of research have shown that agricultural productivity is likely to increase in rangelands across the region with increasing atmospheric carbon dioxide (CO_2) and warming,[3,7,8] with no yield changes likely for small grain crops (for example, wheat) and yield reductions likely for row crops (for example, corn) in dryland croplands.[6] The competitive ability of weeds (primarily perennial forbs such as *Linaria dalmatica* and annual grasses such as *Bromus tectorum*) is likely to increase as well, with corresponding impacts to forage production,[1,2] as phenology is altered[57,58] and the growing season lengthens.[4,5] Forage quality is expected to decline,[3,59,60] and crop yields

are likely to decrease if extreme temperature events (high daytime highs or nighttime lows) occur during critical pollination and grain fill periods.[9]

Numerous lines of research have addressed adaptation strategies for various parts of the agricultural sector[9,61,63,146,147,148]

Major uncertainties

While there is high confidence in future increases in temperature, uncertainties exist as to the changes in extreme events, including the spatiotemporal aspects of high-intensity rainfall events, snowstorms, and hailstorms. Perhaps most important are the uncertainties in the degree of precipitation variability from year to year[35] that influence decision-making calendars for agricultural producers.

Description of confidence and likelihood

There is *very high confidence* that longer growing seasons have already benefited agriculture in parts of the Northern Great Plains. There is *very high confidence* that increases in temperatures and atmospheric CO_2 will *likely* increase production potential for the agricultural sector in the short term (the next 10–20 years) and that current adaptations already being implemented by a subset of producers in this region provide opportunities for assessment, further development, and adoption by the larger population of agricultural managers. There is *very high confidence* that rising temperatures and changes in extreme weather events are very *likely* to have negative impacts on parts of the region. Over the longer-term (through the end of the 21st century), predicted climate changes may require transformative changes in agricultural management, including regional shifts of agricultural practices and enterprises (*very likely*, *high confidence*).[61,64]

Key Message 3

Recreation and Tourism

Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are at risk in a changing climate (*very high confidence*). Rising temperatures have already resulted in shorter snow seasons, lower summer streamflows, and higher stream temperatures and have negatively affected high-elevation ecosystems and riparian areas, with important consequences for local economies that depend on winter or river-based recreational activities (*high confidence*). Climate-induced land-use changes in agriculture can have cascading effects on closely entwined natural ecosystems, such as wetlands, and the diverse species and recreational amenities they support (*very high confidence, likely*). Federal, tribal, state, and private organizations are undertaking preparedness and adaptation activities, such as scenario planning, transboundary collaboration, and development of market-based tools.

Description of evidence base

State-level surveys, conducted roughly every five years, have consistently documented that the public spends millions of days each year (over $30 million in 2011) participating in nature-based recreation activities in the Northern Great Plains (e.g., U.S. Department of the Interior and U.S.

Department of Commerce 2008, 2013a, 2013b, 2014a, 2014b[65,66,67,68,69]). The implications of climate change for outdoor recreation, and tourism more broadly, have been studied extensively around the globe (see summaries in Scott et al. 2012, Rosselló and Santana-Gallego 2014, Brice et al. 2017[101,149,150]). Region-specific studies are only a small subset of this large body of literature, so our understanding of potential impacts of climate change on outdoor recreation in the Northern Great Plains is sometimes inferred from other regions with similar characteristics (e.g., Hari et al. 2006[83]). Region-inclusive studies are available (e.g., Wobus et al. 2017[11]) for the sectors most obviously affected by climate change (such as winter recreation). Our understanding is most complete about the implications of climate change for the ecosystems upon which outdoor recreation in the Northern Great Plains depends.[70] For example, the implications of climate change for wetlands and waterbirds in the Prairie Pothole Region, upon which much bird hunting and bird watching in the region depend,[104,105] have been studied extensively over the past several decades (e.g., Johnson and Poiani 2016, Wright and Wimberly 2013[46,106]). The role of agricultural land-use change (as a function of climate change as well as complex technological, policy, and market factors) in the degradation of wetland function in the region—for example through increased soil erosion and resulting wetland sedimentation or upland habitat fragmentation and resulting increases in waterfowl nest predation—has also been thoroughly assessed (e.g., Rashford et al. 2016, Sofaer et al. 2016[12,109]).

Major uncertainties

Climate change is expected to disrupt local economies that depend on winter-based or river-based recreational activities. However, the magnitudes of these effects are uncertain. This is due largely to uncertainties about the preferences of recreationalists and the extent to which they will adapt by shifting the timing and location of their activities or by substituting towards a different set of recreational activities. For example, although climate change will make it more difficult to supply high-quality downhill skiing opportunities, this effect will be stronger in lower-elevation areas. Therefore, some skiers might adapt by simply traveling to higher-elevation downhill ski areas. Others might compensate for the shorter ski season at their favorite lower-elevation mountain by shifting some of their recreational time to an alternative outdoor activity, such as winter mountain biking. Given the potential diversity of individual preferences for adapting outdoor recreation activities to climate change, it is challenging to project with certainty the future potential impacts to recreation-dependent economies, but the impact will be larger and more immediate for some industries and companies (e.g., low-altitude ski resorts).

Another source of uncertainty is the reliance, in some cases, on scientific studies from other geographic locations to infer what the impacts of climate change might be for ecosystems, species, or recreationalists within the Northern Great Plains. For example, the effects of increased stream temperature on the susceptibility of coldwater fish species to diseases in the region are based largely on studies conducted in European coldwater fisheries.

Regarding wetlands in the Prairie Pothole Region, uncertainty about their abundance in the future arises from uncertainty about future government policies that would either exacerbate or mitigate climate-induced losses. For example, future versions of the Farm Bill may contain language that directly encourages wetland preservation (e.g., through conservation-compliance requirements) or unintentionally leads to wetland degradation (e.g., through higher subsidies for row crop insurance).

Description of confidence and likelihood

We know with *very high confidence* that ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services. We know with *very high confidence* that climate change is *very likely* affecting abiotic factors that influence these ecosystems, such as snowfall, spring snowmelt, runoff, and stream temperatures. There is *high* confidence that these abiotic factors are *likely* to affect high-elevation ecosystems and riparian areas in the Northern Great Plains. Greater confidence could be gained by conducting studies specifically within the Northern Great Plains, as opposed to drawing inferences from studies conducted in other regions of the world with similar characteristics. The consequences of ecosystem changes for local economies in the region that depend on winter-based or river-based recreational activities are currently being debated in the scientific literature, due to uncertainty about potential individual behavioral responses to changes in the recreational environment. Based on a limited number of case studies, effects of climate change on outdoor recreation-based economies are *as likely as not* to be negative, but this is only known with *medium confidence*. We know with *very high confidence*, however, that some natural ecosystems that local economies depend upon—in this specific case, wetlands in the Northern Great Plains—are *likely* to be negatively affected by climate-induced changes in agricultural land use. In turn, we know with *high confidence* that wetland declines will *very likely* harm the diverse species and recreational amenities they support. Uncertainty about future policies that could influence agricultural land-use decisions and wetland conservation outcomes precludes a higher confidence level or higher likelihood.

Key Message 4

Energy

Fossil fuel and renewable energy production and distribution infrastructure is expanding within the Northern Great Plains (*very high confidence*). Climate change and extreme weather events put this infrastructure at risk, as well as the supply of energy it contributes to support individuals, communities, and the U.S. economy as a whole (*likely, high confidence*). The energy sector is also a significant source of greenhouse gases (*very likely, very high confidence*) and volatile organic compounds that contribute to climate change and ground-level ozone pollution (*likely in some areas, very high confidence*).

Description of evidence base

Fossil fuel and renewable energy production/distribution infrastructure is expanding within the Northern Great Plains, including oil and natural gas pipelines, natural gas compressor stations and storage tanks, natural gas processing plants, natural gas-fired power plants, high-voltage power lines and substations, wind farms, and even a new oil refinery and a new biorefinery in recent years (both began operations in 2015).

A number of oil and natural gas pipelines are being constructed or have been completed in recent years. In particular, the Dakota Access Pipeline began commercial service June 1, 2017, transporting crude oil from the Bakken/Three Forks production areas in North Dakota, through South Dakota and Iowa, to Pakota, Illinois. While pipelines are vulnerable to damage or disruption from heavy precipitation events and associated flooding and erosion,[13] their increased use could

eliminate hundreds of rail cars and trucks needed to transport crude every day. This reduces the exposure of these modes of transportation to rising temperatures, heat waves, and floods.[13] Other oil and gas production and distribution infrastructure is similarly vulnerable to heavy precipitation events and flooding.

The region relies on rail lines to transport coal, and these lines are vulnerable to rising temperatures, heat waves, and floods.[13] There is ample evidence of rail line vulnerability to extreme weather.[151]

Damage to thermoelectric power plants and electric power transmission lines from extreme weather such as heat waves and wildfires has been documented, and the risk is expected to increase.[13,152]

The U.S. Department of Energy (DOE) Energy Risk Profiles (1996–2014) highlight the risks to energy infrastructure in the United States from natural hazards. For example, in North Dakota, thunderstorms and lightning had the highest frequency of occurrence and property loss during this timeframe. DOE also has a series of comprehensive documents on U.S. energy sector vulnerabilities to climate change[13,153] that identify important climate-related vulnerabilities for fuel transport, electricity generation, and electricity demand.

There is substantial evidence that the energy sector is a significant source of greenhouse gases that contribute to climate change, in particular from power plants, oil and gas systems, and refineries.[117]

Major uncertainties

Cold waves are projected to be less intense in the future, reducing the risk of disruptions from cold to energy infrastructure.[13]

There is not yet substantial agreement among sources as to how a changing climate will ultimately affect wind resources in the United States in general and in the Northern Great Plains in particular.[153]

Projected increases in precipitation in the Northern Great Plains are likely to benefit hydropower production, but this will vary by location. For example, it is known that in the Columbia River Basin, decreasing summer streamflows will reduce downstream hydropower production, and increasing winter and early spring streamflows will increase production.[13] In the Missouri River Basin, projected seasonal declines in precipitation in the southern and western portion of the region are likely to reduce the water available to generate hydropower.[13]

Biofuel feedstocks from crops and forage grown in the Northern Great Plains are vulnerable to climate change, but the net impacts on biofuel production are uncertain.[13]

It is well understood that ground-level ozone (O_3) is created by chemical reactions between volatile organic compounds in the presence of sunlight and would be exacerbated by climate change. What is less understood is the sensitivity of regional climate-induced O_3 changes, and the science of modeling climate and atmospheric chemistry to understand future conditions.

Description of confidence and likelihood

There is *high confidence* that climate change and extreme weather events will *likely* put energy supply and infrastructure of various types at risk. There is *high confidence* that the energy sector is a *very likely* a significant source of greenhouse gases contributing to climate change. There is *very high confidence* that volatile organic compounds contribute to climate change and ground-level ozone pollution, and it is *likely* that this will worsen in the future in some areas.

Key Message 5

Indigenous Peoples

Indigenous peoples of the Northern Great Plains are at high risk from a variety of climate change impacts, especially those resulting from hydrological changes, including changes in snowpack, seasonality and timing of precipitation events, and extreme flooding and droughts as well as melting glaciers and reduction in streamflows (*likely, very high confidence*). These changes are already resulting in harmful impacts to tribal economies, livelihoods, and sacred waters and plants used for ceremonies, medicine, and subsistence (*very high confidence*). At the same time, many tribes have been very proactive in adaptation and strategic climate change planning (*very likely, very high confidence*).

Description of evidence base

Multiple lines of research have shown that hydrological changes and changes in extremes have resulted in deleterious impacts to Indigenous peoples.[14,18,19,20,23,24,28,121,122,123,124] During times of drought, decreased water availability negatively impacts tribal communities and livelihoods such as ranching, and already stressed water systems and infrastructure do not provide the necessary water to sustain Indigenous communities and reservations.[20,28,154]

Major uncertainties

The impacts of climate change in the Northern Great Plains are expected to increase risks to Indigenous reservations, communities, and livelihoods. However, there is uncertainty about how Indigenous people will be able to respond. Much of this uncertainty is due to unsettled water rights, multijurisdictional complexities, and federal funding and policies.

Description of confidence and likelihood

There is *very high confidence* that rising temperature and increases in flooding, runoff events, and drought are *likely* to lead to increases in impacts to reservations and other Indigenous communities. There is *very high confidence* that climate changes are already resulting in harmful impacts on tribal economies, livelihoods, and culture. However, the actual impacts and response capacities will depend on the response of regulatory systems and funding amounts.

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23 Southern Great Plains

Whooping cranes in the Aransas National Wildlife Refuge in Texas

Key Message 1

Food, Energy, and Water Resources

Quality of life in the region will be compromised as increasing population, the migration of individuals from rural to urban locations, and a changing climate redistribute demand at the intersection of food consumption, energy production, and water resources. A growing number of adaptation strategies, improved climate services, and early warning decision support systems will more effectively manage the complex regional, national, and transnational issues associated with food, energy, and water.

Key Message 2

Infrastructure

The built environment is vulnerable to increasing temperature, extreme precipitation, and continued sea level rise, particularly as infrastructure ages and populations shift to urban centers. Along the Texas Gulf Coast, relative sea level rise of twice the global average will put coastal infrastructure at risk. Regional adaptation efforts that harden or relocate critical infrastructure will reduce the risk of climate change impacts.

Key Message 3

Ecosystems and Ecosystem Services

Terrestrial and aquatic ecosystems are being directly and indirectly altered by climate change. Some species can adapt to extreme droughts, unprecedented floods, and wildfires from a changing climate, while others cannot, resulting in significant impacts to both services and people living in these ecosystems. Landscape-scale ecological services will increase the resilience of the most vulnerable species.

Key Message 4

Human Health

Health threats, including heat illness and diseases transmitted through food, water, and insects, will increase as temperature rises. Weather conditions supporting these health threats are projected to be of longer duration or occur at times of the year when these threats are not normally experienced. Extreme weather events with resultant physical injury and population displacement are also a threat. These threats are likely to increase in frequency and distribution and are likely to create significant economic burdens. Vulnerability and adaptation assessments, comprehensive response plans, seasonal health forecasts, and early warning systems can be useful adaptation strategies.

Key Message 5

Indigenous Peoples

Tribal and Indigenous communities are particularly vulnerable to climate change due to water resource constraints, extreme weather events, higher temperature, and other likely public health issues. Efforts to build community resilience can be hindered by economic, political, and infrastructure limitations, but traditional knowledge and intertribal organizations provide opportunities to adapt to the potential challenges of climate change.

Executive Summary

The Southern Great Plains experiences weather that is dramatic and consequential; from hurricanes and flooding to heat waves and drought, its 34 million people, their infrastructure, and economies are often stressed, greatly impacting socioeconomic systems. The quality of life for the region's residents is dependent upon resources and natural systems for the sustainable provision of our basic needs—food, energy, and water. Extreme weather and climate events have redistributed demands for consumption, production, and supply across the region. Adaptation strategies that integrate climate services and early warning systems are improving our abilities to develop sustainable infrastructure and increase agricultural production, yet include the flexibility needed to embrace any changing demand patterns.

Regional adaptation efforts that harden or relocate critical infrastructure will reduce the risk of climate change impacts. Redesigns of coastal infrastructure and the use of green/gray methodologies are improving future coastal resilience. Energy industry reinvention is ensuring operations and reliability during extreme climatic events. Increasingly robust considerations of economic resilience allow us to anticipate risk, evaluate how that risk can affect our needs, and build a responsive adaptive capacity.

With climate change, terrestrial and aquatic ecosystems, and species within them, have winners and losers. Those that can adapt are "increasers," while others cannot, resulting in impacts to traditional services and the livelihoods of the people

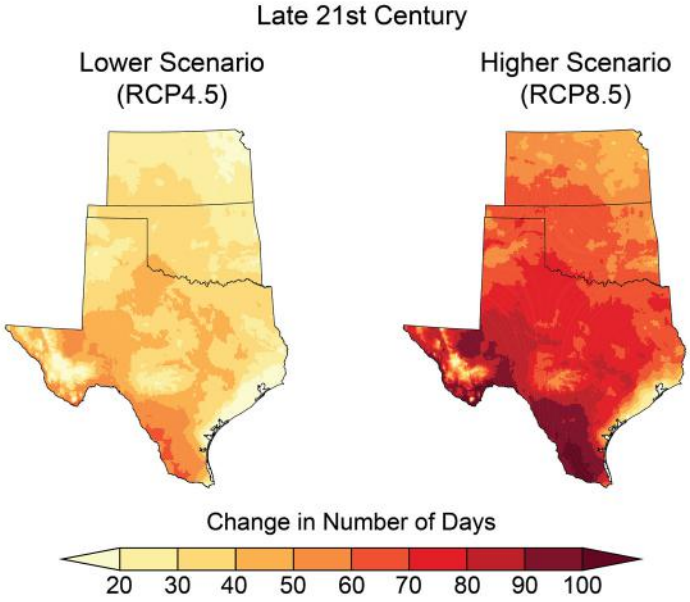
who depend on those resources. The warming of coastal bay waters has been documented since at least the 1980s, and those increases in water temperature directly affect water quality, leading to hypoxia, harmful algal blooms, and fish kills—thus lowering the productivity and diversity of estuaries. Natural wetlands like the playa lakes in the High Plains, which have served for centuries as important habitat for migrating waterfowl, are virtually nonexistent during drought.

Direct human health threats follow a similar pattern of species within our natural ecosystems. Extreme weather results in both direct and indirect impacts to people; physical injury and population displacement are anticipated to result with climate change. Heat illness and diseases transmitted through food, water, and insects increase human risk as temperature rises. Acute awareness of these future impacts allows us to plan for the most vulnerable and adapt through response plans, health forecasting, and early warning strategies, including those that span transboundary contexts and systems.

The impacts of climate change in general become more acute when considering tribal and Indigenous communities. Resilience to climate change will be hindered by economic, political, and infrastructure limitations for these groups; at the same time, connectivity of the tribes and Indigenous communities offers opportunities for teaching adaptably through their cultural means of applying traditional knowledge and intertribal organization. These well-honed connections of adapting through the centuries may help all of us learn how to offset the impacts and potential challenges of climate change.

The role of climate change in altering the frequency of the types of severe weather most typically associated with the Southern Great Plains, such as severe local storms, hailstorms, and tornadoes, remains difficult to quantify.[1,2] Indirect approaches suggest a possible increase in the circumstances conducive to such severe weather,[3] including an increase in the instances of larger hail sizes in the region by 2040,[4] but changes are unlikely to be uniform across the region, and additional research is needed.

Projected Increase in Number of Days Above 100°F



Under both lower- and higher-scenario climate change projections, the number of days exceeding 100°F is projected to increase markedly across the Southern Great Plains by the end of the century (2070–2099 as compared to 1976–2005). *From Figure 23.4 (Sources: NOAA NCEI and CICS-NC)*.

Background

The Southern Great Plains, composed of Kansas, Oklahoma, and Texas, experiences weather that is dramatic and consequential. Hurricanes, flooding, severe storms with large hail and tornadoes, blizzards, ice storms, relentless winds, heat waves, and drought—its people and economies are often at the mercy of some of the most diverse and extreme weather hazards on the planet. These events cause significant stress to existing infrastructure and socioeconomic systems and can result in significant loss of life and the loss of billions of dollars in property.

Climate conditions in the Southern Great Plains vary dramatically from the arid, high-elevation borders with the mountainous states of Colorado and New Mexico on the west, to the humid states of Missouri, Arkansas, and Louisiana in the Mississippi River valley on the east. Average annual precipitation ranges from less than 10 inches in the western reaches of the region to over 60 inches in the southeastern corner (Figure 23.1).

A large west-to-east contrast in surface water availability results, with large reservoirs in eastern parts of the region and few reservoirs in the west. Except for the Missouri River (a portion of the border for the Southern Great

Monitoring Precipitation Across the Southern Great Plains

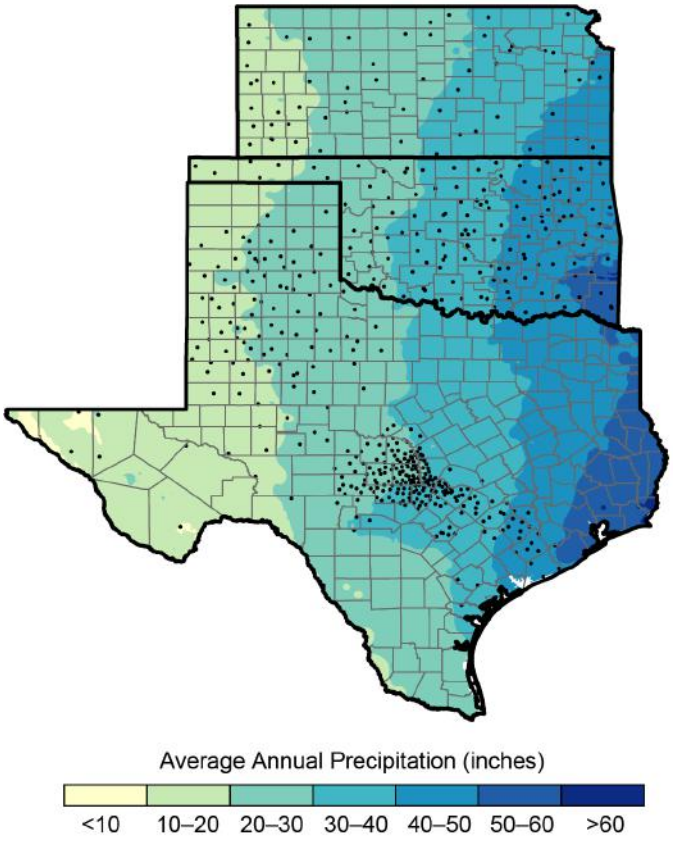


Figure 23.1: The Southern Great Plains is characterized by a pronounced east–west gradient of precipitation, with wetter conditions prevailing to the east and arid conditions to the west. Precipitation monitoring is critical in this region; state-level Mesonet station networks in Kansas, Oklahoma, and Texas are shown here to illustrate a key aspect of current monitoring capacity. Sources: NOAA NCEI, CICS-NC, and ERT Inc. Data from PRISM Climate group, Oregon State University, http://prism.oregonstate.edu, created July 10, 2010.

Plains), the Arkansas River, and the upper reaches of the rivers such as the Rio Grande, rivers in the region do not draw from mountain snowpack and are sensitive to seasonal rainfall amounts. The region is vulnerable to periods of drought, historically prevalent during the 1910s, 1930s, 1950s, and 2010–2015, and periods of abundant precipitation, particularly the 1980s and early 1990s. The region has experienced an increase in annual average temperature of 1°–2°F since the early 20th century, with the greatest warming during the winter months.

With the Gulf of Mexico to its southeast, the coastal Southern Great Plains is vulnerable to hurricanes and sea level rise. Relative sea level rise along the Texas Gulf Coast is twice as large as the global average, and an extreme storm surge in Galveston Bay would threaten much of the U.S. petroleum and natural gas refining capacity. Variations in freshwater flows and evaporation affect the salinity of bays and estuaries along the coast and have the potential to alter coastal ecosystems and affect the fishing industry. Tropical cyclones are also responsible for exceptional rainfall rates in the region. The U.S. record for greatest single-day rainfall is 43 inches, set in Alvin, Texas, in July of 1979, as Tropical Storm Claudette moved through the area. Houston, Texas, in particular, experienced several record-breaking floods in 2015, 2016, and 2017, with Hurricane Harvey rewriting the continental U.S. record for total rainfall from a tropical cyclone. Cedar Bayou, Texas (30 miles from Houston), recorded 51.88 inches of rain during the multi-day onslaught of Hurricane Harvey (see Box 23.1 for further discussion).

Box 23.1: Hurricane Harvey

Hurricane Harvey was a Category 4 hurricane on the Saffir–Simpson scale when it made landfall on the central Texas coast near Rockport late in the evening of August 25, 2017. It then moved inland, stalled, and eventually moved back over the coastal Gulf of Mexico waters before making landfall a final time as a tropical storm several days later in southwestern Louisiana.

Preliminary damage estimates place Harvey as one of the two most costly U.S. natural disasters in inflation-adjusted dollars, rivaling Hurricane Katrina. Flooding from Harvey resulted in the overflow of sewage systems and breaches at numerous waste treatment facilities,[5] resulting in untreated infectious human waste entering surface waters and resulting in a spike in skin and gastrointestinal infections.[6]

Widespread flooding affected dozens of communities, including those in the Houston and Beaumont metropolitan areas. Immediate effects included deaths from drowning and trauma that claimed the lives of at least 63 individuals. Additionally, more than 30,000 people were evacuated. Displacement of patients from their communities and healthcare providers led to interruptions in medical treatment. Texas has one of the lowest rates of health insurance in the country, and more than 11% of the population of Texas is diabetic.[7] Additionally, chronic kidney disease rates in Texas are higher than the national average, with a prevalence of over 17% in the adult population, and 1,524 per one million inhabitants require routine dialysis.[7] In the aftermath of the hurricane, dialysis centers struggled with staffing shortages, and centers in outlying areas worked around the clock to attempt to meet the needs of evacuated patients.[8] Hospitals and pharmacies faced critical shortages of essential medications (including insulin and respiratory inhalers) due to the inability of suppliers to make deliveries. Hospitals faced critical power shortages and loss of indoor air and temperature controls. At least 15 area hospitals evacuated their patients.[9]

Box 23.1: Hurricane Harvey, *continued*

Based on past trends and recent sea surface temperatures, the heaviest rainfall amounts from intense storms such as Harvey are about 5%–7% greater now than what they would have been a century ago.[1] As discussed in detail in Chapter 2: Climate, several studies have already quantified the human contribution to the record-breaking rainfall associated with Hurricane Harvey. Additional information is available in Chapter 17: Complex Systems, Box 17.1.

In an attempt to recover from Hurricane Harvey and help prepare for future hurricanes, leaders in government, education, business, and nonprofit organizations gathered to identify unmet needs across all of the affected communities. For example, the Rebuild Texas Fund has a special focus on serving low-income communities and their most vulnerable members (https://www.rebuildtx.org). It was developed to support organizations that provide services in four focus areas: health and housing, schools and child care, workforce and transportation, and capital for rebuilding small businesses.

Figure 23.2: Texas Army National Guard assisting in flood rescues associated with Hurricane Harvey, August 27, 2017. Photo credit: Lt. Zachary West, Texas National Guard.

Box 23.1: Hurricane Harvey, *continued*

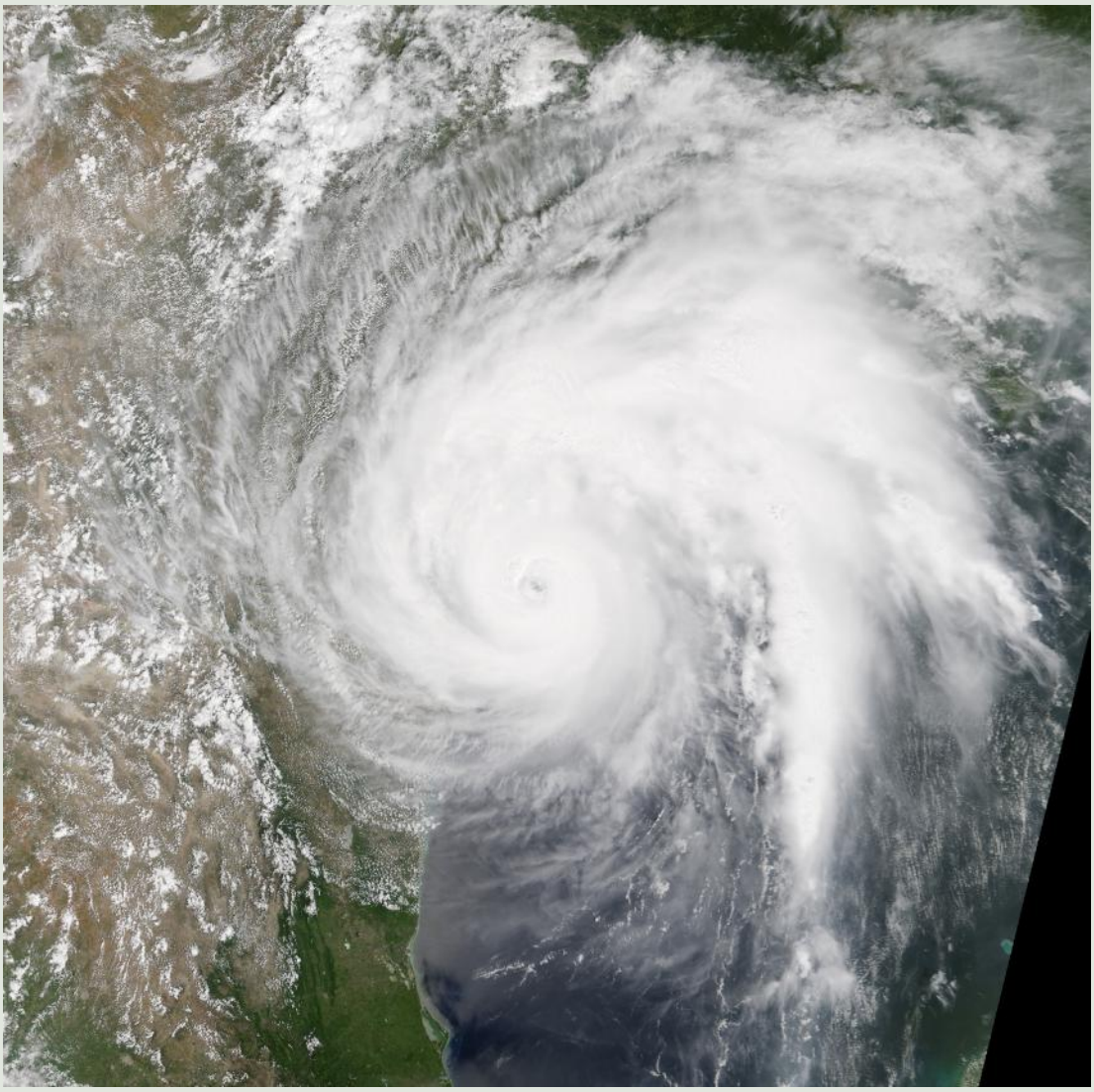


Figure 23.3: This visible satellite image shows Hurricane Harvey approaching the Texas coast on August 25, 2017. Image credit: NASA Earth Observatory.

Over the past 50 years, significant flooding and rainfall events followed drought in approximately one-third of the drought-affected periods in the region when compared against the early part of the 20th century.[10] Understanding this rapid swing from extreme drought to flood is an important and ongoing area of research in the region. As major metropolitan areas in the region continue their rapid population growth, overall exposure to extreme rainfall events will increase. Yet, even while record-breaking flooding events increased over the past 30 years, the Southern Great Plains experienced an overall decrease in flood frequency,[11] possibly related to the decrease in total precipitation over the same period.

The Southern Great Plains is a critical thoroughfare for rail and road freight, supports numerous ocean and river ports within its borders, and is a major energy producer and exporter.[12] Combined, the three-state region accounts for 25% of all U.S. energy production. The world's largest oil-storage tank facility is located in Cushing, Oklahoma, with 13% of total U.S. storage and a convergence of several major pipelines. More than 550,000 miles of roads connect rural and urban communities and serve as vital infrastructure supporting state and local economies.[13,14,15] The vast and dispersed nature of the region's infrastructure makes investment in maintenance and rehabilitation of deficient and aging infrastructure difficult. Infrastructure is typically designed to withstand historical climate extremes and is exposed to the environment year-round. Therefore, as the intensity and frequency of climate-related extremes (such as heat, drought, flooding, and severe storms) increase, impacts to the region are usually adverse and costly. The Southern Great Plains ranks near the top of states with structurally deficient or functionally obsolete bridges, while other bridges are nearing the end of their design life.[16,17,18] Road surface degradation in Texas urban centers is linked to an extra $5.7 billion in vehicle operating costs annually (dollar year not reported).[15] The region has tens of thousands of dams and levees; however, many are not subject to regular inspection and maintenance and have an average age exceeding 40 years.[16,17,18] Most state and local budgets are unable to meet the funding needs for infrastructure improvements, particularly in rural towns where funding is largely derived from municipal revenue. In urban centers, population growth is anticipated to require expansion of transportation infrastructure and services and revisions to flood control structures and policies[16,17,18] and result in increased water resource needs and a growth in building demand.[19,20]

Understanding the potential for future changes in the frequency and severity of weather events and their impacts will ultimately determine the sustainability of economies, cultures, ecosystems, health, and life in the region. Over the past two decades, state and local governments have invested in the creation of weather monitoring networks ("Mesonets") that are designed to measure important weather and climate parameters (Figure 23.1).[21] Mesonet stations are critical infrastructure required to establish the long-term climate record for the region. Mesonet observations have been especially critical for predicting and preparing for extreme weather events like droughts, floods, ice storms, and severe convective storms, as well as for developing value-added products. These data are used daily by decision-makers, public safety officials, educational institutions, the agricultural sector, and researchers, generating societal and economic benefits that greatly exceed the investments made in these systems.[22,23]

Projections

Climate change is expected to lead to an increase in average temperatures as well as frequency, duration, and intensity of extreme heat events and a reduction in extreme cold events. Annual average temperatures in the Southern Great Plains are projected to increase by 3.6°–5.1°F by the mid-21st century and by 4.4°–8.4°F by the late 21st century, compared to the average for 1976–2005, and are dependent on future scenario, with higher levels of greenhouse gas emissions leading to greater and faster temperature increases. Extreme heat will become more common. Temperatures similar to the summer of 2011 will become increasingly likely to reoccur, particularly under higher scenarios. By late in the 21st century, if no reductions in emissions take place, the region is projected to experience an additional 30–60 days per year above 100°F than it does now (Figure 23.4).[24]

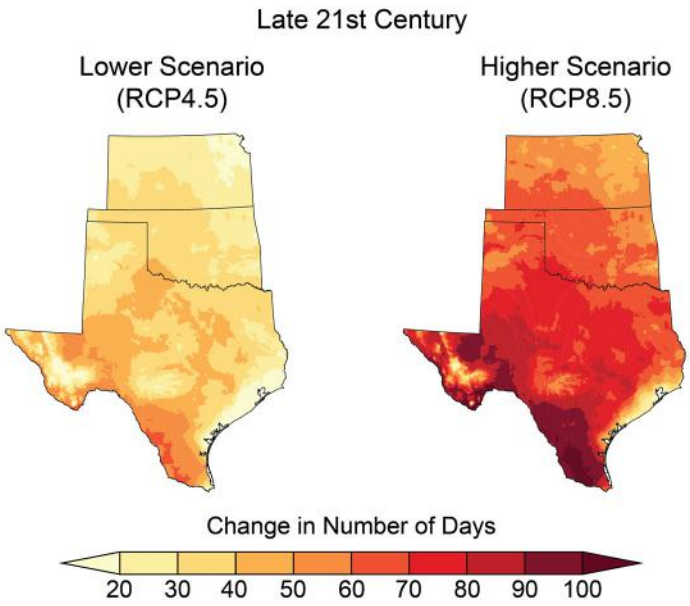


Figure 23.4: Under both lower- and higher-scenario climate change projections, the number of days exceeding 100°F is projected to increase markedly across the Southern Great Plains by the end of the century (2070–2099 as compared to 1976–2005). Sources: NOAA NCEI and CICS-NC.

The role of climate change in altering the frequency of the types of severe weather most typically associated with the Southern Great Plains, such as severe local storms, hailstorms, and tornadoes, remains difficult to quantify.[1,2] Indirect approaches suggest a possible increase in the circumstances conducive to such severe weather,[3] including an increase in the instances of larger hail sizes in the region by 2040,[4] but changes are unlikely to be uniform across the region, and additional research is needed.

Along the Texas coastline, sea levels have risen 5–17 inches over the last 100 years, depending on local topography and subsidence (sinking of land).[25] Sea level rise along the western Gulf of Mexico during the remainder of the 21st century is likely to be greater than the projected global average of 1–4 feet or more.[26] Such a change, along with the related retreat of the Gulf coastline,[27] will exacerbate risks and impacts from storm surges.

Average annual precipitation projections suggest small changes in the region, with slightly wetter winters, particularly in the north of the region, and drier summers.[1] However, the frequency and intensity of heavy precipitation are anticipated to continue to increase, particularly under higher scenarios and later in the century.[1] The expected increase of precipitation intensity implies fewer soaking rains and more time to dry out between events, with an attendant increase in soil moisture stress. Studies that have attempted to simulate the consequences of future precipitation patterns consistently project less future soil moisture, with future conditions possibly drier than anything experienced by the region during at least the past 1,000 years.[28]

While past hydrologic extremes have been driven largely by climate variability, climate change is likely to exacerbate aridity in the Southern Great Plains, largely associated with drying soils due to increased evapotranspiration caused by higher temperatures.[1,29]

Key Message 1

Food, Energy, and Water Resources

Quality of life in the region will be compromised as increasing population, the migration of individuals from rural to urban locations, and a changing climate redistribute demand at the intersection of food consumption, energy production, and water resources. A growing number of adaptation strategies, improved climate services, and early warning decision support systems will more effectively manage the complex regional, national, and transnational issues associated with food, energy, and water.

Food, energy, and water systems are inseparable. Any change in demand for one will impact demand on the other two. The quality of life of the 34 million people residing in the Southern Great Plains is dependent upon the resources and natural systems for the sustainable provision of food, energy, and water. At least 60% of the region's population is clustered around urban centers, which are experiencing population growth that exceeds that of rural communities. The remaining population is spread across vast areas of rural land.[14,30,31,32,33] As the population in the region grows, rapid urbanization and economic development opportunities will drive an increase in the demand for food, energy, and water. Water is used in every aspect of agricultural production and electricity generation. Energy is required to extract and deliver water of sufficient quality for diverse human and agricultural use, as well as healthy consumption and wastewater treatment. Both water and energy are required to irrigate and process agricultural products and livestock to feed the region's increasing population. The complex interdependencies at the food–energy–water nexus create enormous challenges.

When severe drought affected the Southern Great Plains in 2011, limited water availability constrained the operation of some power plants and other energy production activities. Contention for water developed between consumers associated with the food–energy–water nexus. The recent boom in domestic unconventional oil and gas development brought on by hydraulic fracturing and horizontal drilling represents another stressor to this nexus. This development has added complexity to the regional dialog about the relationship between food, energy, and water resources.

Superimposed on the existing complexities at the intersection of food, energy, and water is the specter of climate change. During 2010–2015, the multiyear regional drought severely affected both agricultural and aquatic ecosystems. One prominent impact was a reduction of irrigation water released for the Texas Rice Belt farmers on the Texas coastal plains, as well as a reduction in the amount of water available to meet instream flow needs in the Colorado River and freshwater inflow needs to Matagorda Bay. The Lower Colorado River Authority (LCRA), through its Water Management Plan (WMP), balances the needs of competing water demands in the Lower Colorado River Basin of Texas. Depending upon the amount of water stored in lakes, the WMP requires that LCRA reduce or cut off interruptible stored water for most downstream agriculture so firm water supplies are available to meet the basic needs of cities, businesses, and industries during drought.

In one year, planted acres of rice in Matagorda County, Texas, dropped from 22,000 acres to 2,100 acres.[34] The ripple effect on the local economy was severe, with a 70% decline in sales of farm implements and machinery. Some family-owned establishments that had survived for decades closed permanently.[35] Irrigation strategies shifted from river-based to pumping

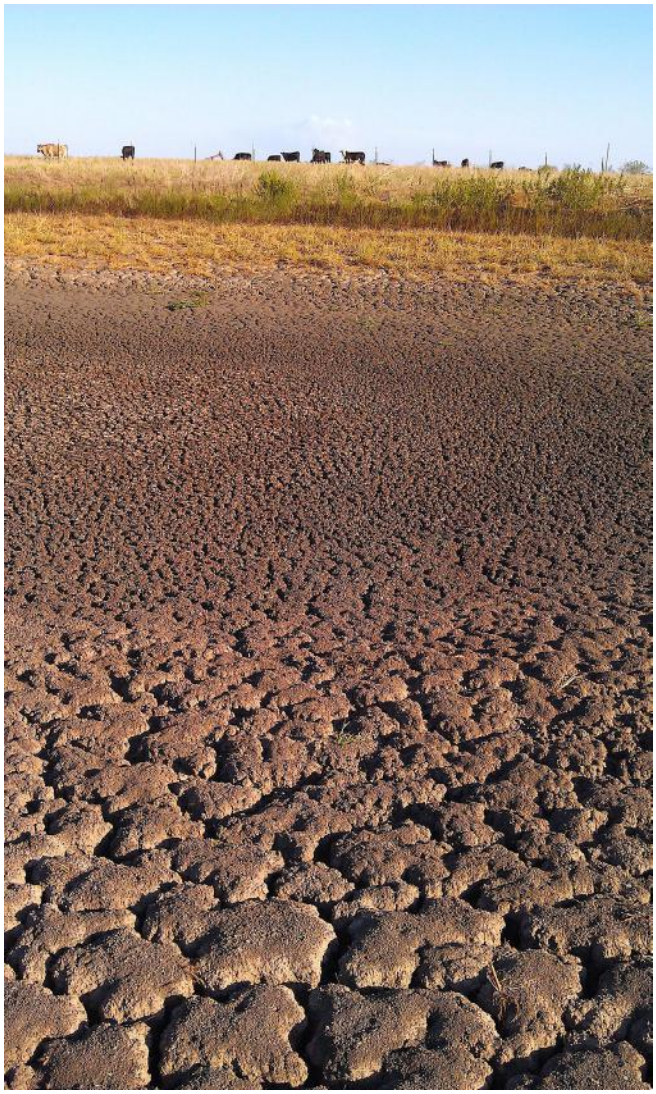


Figure 23.5: The photo shows the drought impact on a stock pond near Kurten, Texas, in 2011. Photo credit: John Nielson-Gammon.

water from the Gulf Coast Aquifer, and dozens of new wells were drilled. Drilling water wells then resulted in declining groundwater levels, adding stress to water levels that had historically been falling in the region.[36] Some farmers attempted to adapt by making the difficult transition to other crops such as corn. However, when flooding rains inundated the region in 2016, 15% of the corn crop was swept away in flood waters.[37] Thus the 2010–2015 drought simultaneously affected agriculture, energy, recreation, and economic activity, eventually leading to increased groundwater development and potential future overexploitation. Projected increases in drought duration and severity imply even more pervasive direct and indirect effects. These impacts might have been even more severe had it not been for adaptation actions taken by the City of Austin, including implementation of drought contingency plans and water-use cutbacks in coordination with the City Council and community.

Climate change has significant negative impacts on agriculture in the United States, causing substantial economic costs (Ch. 10: Ag & Rural).[38,39] The effects of drought and other occurrences of extreme weather outside the Southern Great Plains also affect the food–energy–water nexus in the region. The neighboring Southwest region is especially vulnerable to climate change due to its rapidly increasing population, changing land use and land cover, limited water supplies, and long-term drought (Ch. 25: Southwest).[40] States in the Southern Great Plains import over 20% of their food-related items from Arizona, and El Paso, Texas, receives 25% percent of its consumable foods (mostly vegetables) and 18% of its animal feed supplies from Arizona.[41] In addition, relationships across the border of the Southern Great Plains with Mexico will be critical to a better understanding of the food–energy–water nexus (see Case Study "Rio Grande Valley and Transboundary Issues") (see also Ch. 16: International, KM 4).

Case Study: Rio Grande Valley and Transboundary Issues

In the U.S.–Mexico transboundary region of the Southern Great Plains, no hydrologic resource is more critical than the Rio Grande and its attendant tributaries. Partnered, binational management of the basin's water supply is essential to supporting the agricultural, industrial, and community infrastructure in place along the Rio Grande valley. Proactive and collaborative water management strategies allow for effective flood control, mitigation of drought impacts, and maximization of water quality, among other benefits.[42]

The Rio Grande Gorge near Taos, New Mexico. Photo credit: © flickr.com/josephmccowie.

The Rio Grande is highly sensitive to variations and changes in the climate of the Southern Great Plains, where changes can have marked impacts on the valley's extensive agricultural productivity.[43,44] Increasing regional temperatures,[45] consistent with global trends, will enhance the severity of drought impacts via the acceleration of surface water loss driven by evaporation, particularly in large Rio Grande reservoirs such as Lake Amistad. Changes in regional precipitation patterns, including observed increases in extreme rainfall events as part of a regional "dipole" dry-wet-dry-again pattern,[10] will affect both drought and flood occurrence and intensity along the Rio Grande channel. Other climate-driven impacts, such as changes in wildfire frequency[46] and increased vulnerability to heat events,[40] will further challenge the preparedness and resilience of communities on both sides of the border.

A growing number of adaptation strategies[47] and an increasing provision of regional climate services in the Southern Great Plains[48] bode well for an improved future ability to effectively manage the Rio Grande's transboundary water interests. This is particularly true in the context of early warning decision support systems. Frequently, extreme weather and climate events, such as the 2011–2012 La Niña and 2015–2016 El Niño episodes, serve as catalyzing opportunities to develop new and refine existing information delivery pathways from climate services providers to stakeholder audiences. One recent application in the Rio Grande transboundary region is bilingual seasonal climate outlooks and impact assessments,[49] which are utilized by stakeholders to strengthen regional drought and wildfire outlooks[46] and which augment other ongoing efforts to strengthen bilingual climate services delivery.[50]

Case Study: Rio Grande Valley and Transboundary Issues, *continued*

Highlighting Seasonal-Scale Extreme Events in a Transboundary Setting

AT A GLANCE

1. **New Mexico, North Texas**
Severe to extreme drought conditions developed over the past month, and drought is likely to persist in these regions through May.

2. **Rio Grande/Bravo Region**
High fuel loads from warm, dry conditions, coupled with the increasing frequency of wind events common during early spring in the region, will increase the risk of intense, fast-spreading fires through April.

3. **New Mexico, North Texas**
Precipitation was 0-25% of average from November – January.

UN VISTAZO

1. **Nuevo México, Norte de Texas**
Condiciones severas a extremas de sequía se desarrollaron durante el mes pasado, y es probable que la sequía persista en estas regiones hasta mayo.

2. **Región de Rio Grande / Bravo**
Las altas cargas de combustible provenientes de las condiciones cálidas y secas, junto con la frecuencia cada vez mayor de los eventos de viento comunes a comienzos de la primavera en la región, aumentarán el riesgo de incendios intensos y de rápida propagación hasta abril.

3. **Nuevo México, Norte de Texas**
La precipitación fue 0-25 % del promedio de noviembre a enero.

Figure 23.6: Shown here are the English- and Spanish-language versions of the February 2018 Climate Assessment for the Southwest Rio Grande-Bravo Climate Impacts and Outlook "At a Glance" summary. Source: Garfin et al. 2018.[44,51]

The 2017 Texas State Water Plan[52] indicates that the growing Texas population will result in a 17% increase in water demand in the state over the next 50 years. This increase is projected to be primarily associated with municipal use, manufacturing, and power generation, owing to the projections of population increase in the region. Likewise, the Oklahoma Water Plan indicates that water use projections in Oklahoma are expected to increase by 21% for municipal use, 22% for agricultural use, and 63% for energy use.[53] The Kansas Water Plan's preliminary assessment of projected water demand in Kansas also shows an increase of 20%, but with the expected variability depending upon rural versus urban areas.[54] Throughout much of western Kansas, western Oklahoma, and the Texas Panhandle, groundwater from the Ogallala Aquifer is the dominant water source,[17,55] benefitting the agricultural sector in particular. This resource is known to be shrinking faster than it is replenishing, and some portions are likely to become an insufficient source or become completely depleted within the next 25 years, particularly at its southernmost extent.[17] Drought more persistent than that experienced in the region's recent history would trigger large social and economic consequences, including shifting agriculture, migration, rising commodity prices, and rising utility costs.[20]

The importance of groundwater as a resource will increase under a changing climate as the intensification of hydrologic extremes decreases the reliability of precipitation, soil moisture, and surface water, and as surface water supplies are becoming increasingly over-allocated.[56,57,58]

Research into the food–energy–water nexus is in its early stages and historically tends to examine only one or two components.[59,60,61,62,63,64,65] It is clear that tradeoffs and cascading complexities exist between sectors, and changes in one sector are likely to propagate through the entire system (Ch. 17: Complex Systems). There are significant gaps in the scientific understanding regarding the role that climate change will play as a disruptive force and a threat to food, energy, and water security.[60,63,66,67,68]

Wind turbines near Kansas farmland. Photo credit: © flickr.com/Kansas State Research and Extension.

Case Study: The Edwards Aquifer

The Edwards Aquifer is a "karst" aquifer, composed of limestone and characterized by solution features such as large pores, caves, sinkholes, and conduits that channel groundwater flow. The Edwards provides groundwater to the central Texas region. It serves more than two million people, including the cities of San Antonio, San Marcos, and Austin, which are three of the fastest-growing cities in the country.[69] The aquifer is a source of water for drinking, industry, agriculture, livestock, and recreation. In particular, San Antonio relies nearly entirely on the Edwards for its drinking water. The aquifer is also a habitat for a number of endemic and endangered species. As a shallow karst aquifer, the Edwards is especially sensitive to climate change. Its shallow depth and karst features allow for rapid infiltration and recharge during wet periods, and discharge is similarly responsive, making the Edwards vulnerable to climate extremes of droughts and floods. This high susceptibility and exposure to climate change is a major challenge for managing the Edwards Aquifer as a resource.[70] The probable impacts of climate change for the Edwards Aquifer include a decrease of water supply during droughts, a degradation of habitat for species of concern, economic effects, and the interconnectivity of these impacts. These climate change impacts will be exacerbated in central Texas's rapidly urbanizing regions, as increasing impervious cover will affect water quality and rates of runoff and recharge.

Water availability and demand: The population of Texas is projected to grow by more than 70% between 2020 and 2070, with the majority of the increase projected to occur in urban centers.[52] Increased demand for water will come from municipal, power generation, agriculture, manufacturing, and livestock uses.[52] Over this same period, water availability in the U.S. Southwest is projected to decrease due to a shift to a more drought-prone climate state.[28,71] History shows that increases in population and pumpage from the Edwards led to unsustainable use of water from the aquifer during the drought of the 1950s.[72] The lessons learned from the 1950s drought and the more intense 2011 drought provide a well-suited application for models of how the aquifer and associated ecosystems will respond to further climate change.[73]

Cross Section of Edwards Aquifer

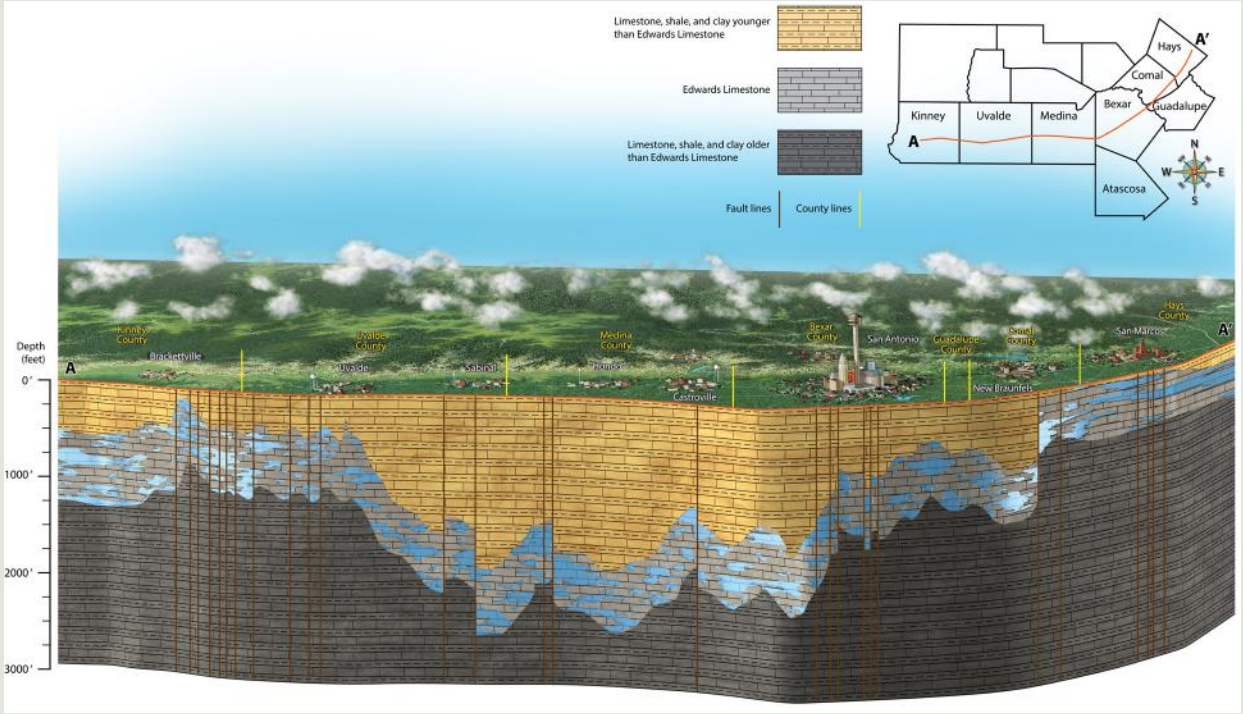


Figure 23.7: Key characteristics of the Edwards Aquifer, such as relative shallowness and karst features, make it vulnerable to the impacts of both climate variability and climate change. Its importance as a major supplier of groundwater in central Texas makes these vulnerabilities even more pronounced. Source: Edwards Aquifer Authority.[79] Used with permission.

Case Study: The Edwards Aquifer, *continued*

Habitat: Plants and animals are sensitive to a variety of changes related to the Edwards Aquifer groundwater system, including changes in habitat, water levels, spring flows, and water quality. An example of the last is an analysis of dissolved oxygen concentrations (DO) in water in Barton Springs, a major point of discharge from the Edwards Aquifer. Most notable are water quality effects on the Barton Springs salamander (*Eurycea sosorum*), a federally listed endangered species native to these springs. An analysis of DO, discharge, and temperature measurements at the springs indicates that low DO episodes that correspond to salamander mortality could result from 1) lower discharge from the springs resulting from increased water withdrawals or decreased recharge as a result of drought, and/or 2) increased water temperature as a result of climate change.[74] A key challenge is understanding and modeling the extent to which endangered and native species can be protected in their habitats associated with the aquifer.[73,75,76]

Impacts: Dramatic drawdowns of groundwater levels by human activity combined with climate change in many regions illustrate the challenges of the nonrenewable nature of groundwater and the multiple dependencies of some ecosystems and agricultural systems on groundwater.[77] Multiple, integrated solutions will be needed to address the impacts on the Edwards Aquifer. These will necessarily involve ways to increase supply through technological approaches, such as desalination of brackish groundwater and aquifer storage and recovery; ways to decrease demand, such as conservation and regulation; and ways to reduce the impact of urbanization through sustainable design. For example, The Edwards Aquifer Recovery Implementation Program Habitat Conservation Plan[78] balances water pumping and use of the aquifer with protection of eight federally listed threatened and endangered species that depend on San Marcos Springs and Comal Springs, two of the largest springs in the southwestern United States. The plan incorporates a number of innovative water supply strategies including Aquifer Storage and Recovery and advanced water conservation, along with market-based solutions for voluntary suspension of groundwater pumping rights during drought periods.

Key Message 2

Infrastructure

The built environment is vulnerable to increasing temperature, extreme precipitation, and continued sea level rise, particularly as infrastructure ages and populations shift to urban centers. Along the Texas Gulf Coast, relative sea level rise of twice the global average will put coastal infrastructure at risk. Regional adaptation efforts that harden or relocate critical infrastructure will reduce the risk of climate change impacts.

Climate change is anticipated to lead to higher average temperatures year-round and an increase in the frequency of very hot days (days with maximum temperatures above 100°F), with the number of such days possibly doubling by mid-21st century (Figure 23.4).[80] An increase in temperatures is *virtually certain* for the Southern Great Plains. Longer, hotter summers will place strain on cooling systems and energy utilities, road surfaces, and water resources, particularly during drought, although warmer winters are likely to reduce heating demands and winter road maintenance costs. The rate of temperature rise will be especially large within urban centers due to possible intensification of the urban heat island (UHI) effect, although the degree of heating will likely vary by city, and it is difficult to obtain precise quantitative estimates. Warmer temperatures will likely lead to an increase in evaporation and therefore an increase in moisture in the air[81,82] and an increase in heat stress, especially during the summertime.[83] During excessive heat in July 2011, downtown

Dallas experienced late-evening temperatures 6.1°F higher than rural Kaufman, Texas, 36 miles away.[84] Population growth, increased urban density, and expansion will intensify the UHI effect for many Southern Great Plains cities, necessitating more energy use for cooling. This strains energy utilities and can further enhance the UHI effect.[85] If prolonged power failure occurs during high heat conditions, the impact to human health and comfort is projected to be notably more detrimental in a warmer climate.[86]

Increased aridity (or dryness) is also projected for the Southern Great Plains with climate change, due to enhanced evapotranspiration and depleted soil moisture associated with increased temperatures.[1,29] In the past, drought conditions have decreased surface water availability (such as from reservoirs), leading to an increase in the use of groundwater. In some cases, new pipelines were needed and water had to be imported.[20] Compounding infrastructure challenges for the region include aging and over-capacity water pipelines.[53] The Texas Water Development Board[87] projected that by 2060, municipal water use will increase to 41% of available supply (versus 9% in 2010). Therefore, a record drought scenario occurring in 2060 would result in as much as half of the state's population facing a water supply shortage. Additionally, water infrastructure can be damaged by drought. During summer 2011, water main breaks were common, with 200 breaks in Fort Worth, Texas, in one month and over 1,000 in one month in Houston, Texas,[20] associated with shrinkage of clay soil, a common soil type throughout the Southern Great Plains. Soil shrinkage can damage both surface and subsurface infrastructure, including roads, water and sewer lines, and building foundations. Periods of abundant precipitation followed by drought and high temperatures are also linked to increased wildfire activity in the region.[88] Texas experienced several major wildfire outbreaks during the drought of 2011, including the Bastrop Fire that destroyed more than 1,500 homes. More recently in 2016 and 2017, fires in Kansas and Oklahoma have exceeded 400,000 acres and were among the largest in the region's history. These events killed thousands of cattle, contributed to several human fatalities, and damaged, displaced, or isolated rural communities.[89] Model simulations indicate that wildfire risk will increase throughout the region as temperatures rise, particularly in the summer, and the duration of the fire season increases.[90]

Following the abrupt end to the persistent drought in 2015, the region suffered extensive damage associated with river and flash flooding.[10,91,92] Precipitation totals for a 120-day period during the spring of 2015 in south-central Oklahoma were above 40 inches, approximately the average annual amount in many locations,[93,94] largely associated with multiple episodes of very heavy rain. Numerous state and U.S highways experienced regional detours or closures.[94] A rockslide on Interstate Highway 35 closed portions of the road for several weeks.[94,95] Flooding in Oklahoma and Texas caused an estimated $2.6 billion in damage in 2015,[95] with $1 million in emergency relief funds provided by the U.S. Department of Transportation's Federal Highway Administration to assist in the repair of damaged roads.[96] The increasing frequency of extreme precipitation that is projected by climate models is anticipated to contribute to further vulnerability of existing highway infrastructure, although the magnitude and timing of projected precipitation extremes remain uncertain.[1]

Changing precipitation frequency and increases in the magnitude and frequency of heavy precipitation will place more stress on existing water resource infrastructure. The region has a large number of older dams and levees, many of which have received poor grades from

the American Society of Civil Engineers.[16,17,18] Between 1982 and 2012, 82 dams failed in Texas, and during 2015 the high-hazard Lewisville Dam was of concern due to observed seepage.[18,97] As climate conditions continue to change, rare events such as 100-year floods (those that currently have a 1% chance of occurring in any given year) are likely to become more common.[1,29] Future extremes may exacerbate flooding and wear and tear on existing flood control infrastructure and will necessitate revisions to design standards for flood infrastructure and a reevaluation of floodplains. Floodplain management and mitigation of flooding are currently left largely to local governments and cities and are thus reliant on local funding and resources for successful implementation.[16,17,18] While there are clear implications of more variable and extreme precipitation on infrastructure, the precise links between specific events and their resulting damage are uncertain as most infrastructure is exposed to both climatic and non-climatic stressors whose effects are difficult to separate without a high degree of monitoring.

As the energy industry undergoes, to some extent, a reinvention, it is taking climate and extreme weather events into consideration in design, operations, and reliability. An Edison Electric Institute (2008) study estimated that by 2030, the U.S. electric utility industry will need to make a total infrastructure investment of between $1.5 trillion and $2.0 trillion, of which transmission and distribution investment is expected to account for about $900 billion.[98] These investments increasingly include renewable energy and distributed generation, smart grid technologies, and storage. From 2008 to 2013, the amount of electricity generated from wind has more than tripled and the amount from solar has increased more than tenfold.[99] These enhancements would need to be reliable (able to operate within limits so that instability, uncontrolled events, or cascading failures do not result if there is a disturbance), resilient (able to adapt to changing conditions and withstand and rapidly recover from disruptions), safe, flexible, and affordable.

Coastal regions are among the most vulnerable to climate change due to their direct exposure to rising sea levels and damaging storm surge. Global mean sea level is very likely to rise by 1–4 feet (0.3–1.3 m) by 2100 relative to 2000 levels. Under certain future conditions, a rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed (Ch. 2: Climate, KM 4). Since the early 20th century, areas of the Texas coast have experienced sea level rise (SLR) higher than the global average, associated with extraction of both fossil fuels and groundwater.[25] Within Texas alone, 1,000 square miles of land is within 5 feet of the high tide line, including $9.6 billion in current assessed property value and homes to about 45,000 people. Sensitive assets include 1,600 miles of roadway, several hospitals and schools, 4 power plants, and 254 EPA-listed contamination sites (hazardous waste and sewage).[100] Up to $20.9 billion in coastal property is projected to be flooded at high tide by 2030, and by 2050, property values below the high-water mark are projected to be in excess of $30 billion, assuming current trends of greenhouse gas emissions.[101] The coastline in the vicinity of Galveston and Texas City is also a critical oil refining and transport hub. SLR will affect numerous coastal assets, including residential communities, roads, waterways, and energy generation facilities, and move the risk of damaging storm surge well inland of present areas of impact. With 2 feet of SLR, cities such as Galveston and Corpus Christi will be exposed to more frequent flooding.[100,102,103,104] Disruption to coastal oil-refining facilities can cause cascading failures throughout the region, including fuel shortages and higher

prices. Saltwater intrusion of aquifers has been observed in the Gulf Coast Aquifer, the second most utilized aquifer in Texas, which supports 8 million people. Although this was in part associated with heavy pumping,[105] the Gulf Coast Aquifer remains vulnerable to further saltwater intrusion resulting from SLR and storm surge exacerbated by climate change.[106]

Due to the historical frequency of drought, water conservation activities are already recognized as important and encouraged in many municipalities. Common strategies include rainwater harvesting, encouraging improved residential water-use efficiency, water audits, and restricted water use in times of drought.[20] Other proactive measures currently in place in some communities aim to mitigate longer-term risks and involve wastewater treatment and reuse, aquifer storage and recovery, and desalination (see Case Study "Meeting Current and Future Water Needs in El Paso, Texas").[20]

Climate change is likely to require modification and updating of design standards in order to accommodate changes in risk that cannot be accounted for based on history. For example, in transportation design, these modifications might include changing the minimum and maximum temperature rating for binders used in asphalt roads to improve durability; structural modifications to bridges to meet the demands of higher summer temperatures; updating the data used for calculating flooding of dams and neighborhoods; restricting rail speeds during hot temperatures; and shifting timing of maintenance activities. Many technological solutions exist or are in development to build resilience to these climate-related challenges. However, the aforementioned stressors and budgetary challenges will continue to present notable challenges to adaptive capacity in the Southern Great Plains (Ch. 12: Transportation).

Many studies have documented economic impacts of climate change on different sectors in the United States).[1111,112,113,114,115] For example, predictive analyses estimate that climate change and coastal development will cause hurricane damage to increase faster than the U.S. economy is expected to grow. The number of people expected to face substantial damage will, on average, increase more than eightfold over the next 60 years.[116] Although economic analyses for specific regions, sectors, and states in the Southern Great Plains are currently limited, active ongoing research is beginning to produce critical metrics regarding the socioeconomic impacts of climate change at regional scales.[117]

The role of economics is increasingly recognized as being critical for advancing the resilience of households, businesses, and local governments, and also for the broader economic adaptation of entire regions. Establishing economic resilience in a local business or a regional economy requires the ability to anticipate risk, evaluate how that risk can impact key economic assets, and build a responsive adaptive capacity. At the regional or community level, economic development practitioners can build capacity for economic resilience.

Case Study: Meeting Current and Future Water Needs in El Paso, Texas

El Paso, Texas, is vulnerable to drought, being situated in the Chihuahuan Desert and with a growing population and limited water resources derived largely from the Rio Grande and regional aquifers. Average annual rainfall is only around 9 inches. The city continues to be a part of the Rockefeller Foundation's 100 Resilient Cities initiative. Prior to, and as part of, El Paso's ongoing climate adaptation planning, the city's water utility program implemented programs on water conservation, reclamation, and supply diversification. In 2007, the city completed construction of the 27.5 million-gallon-per-day Kay Bailey Hutchison Desalination Plant. The desalination is applied to previously unusable brackish waters in the Hueco Bolson Aquifer. Conversion of this brackish water to freshwater increased El Paso's water utilities' production by 25%.[107] The plant is designed to run at capacity only when needed, such as in times of drought. While desalination is expensive due to use of energy-intensive reverse osmosis, the plant was found to be more cost effective in the long term compared with importing water from remote sources. A climate change analysis of the future viability of this infrastructure suggested that it could meet the needs of the city through the next 50 years.[108] Across Texas, brackish water is abundant, estimated at 2.7 billion acre-feet, and an expansion of desalination is recommended in the state's 2017 Water Plan.[109] There are currently 44 public water supply desalination plants in Texas.

Texas Desalination Plants

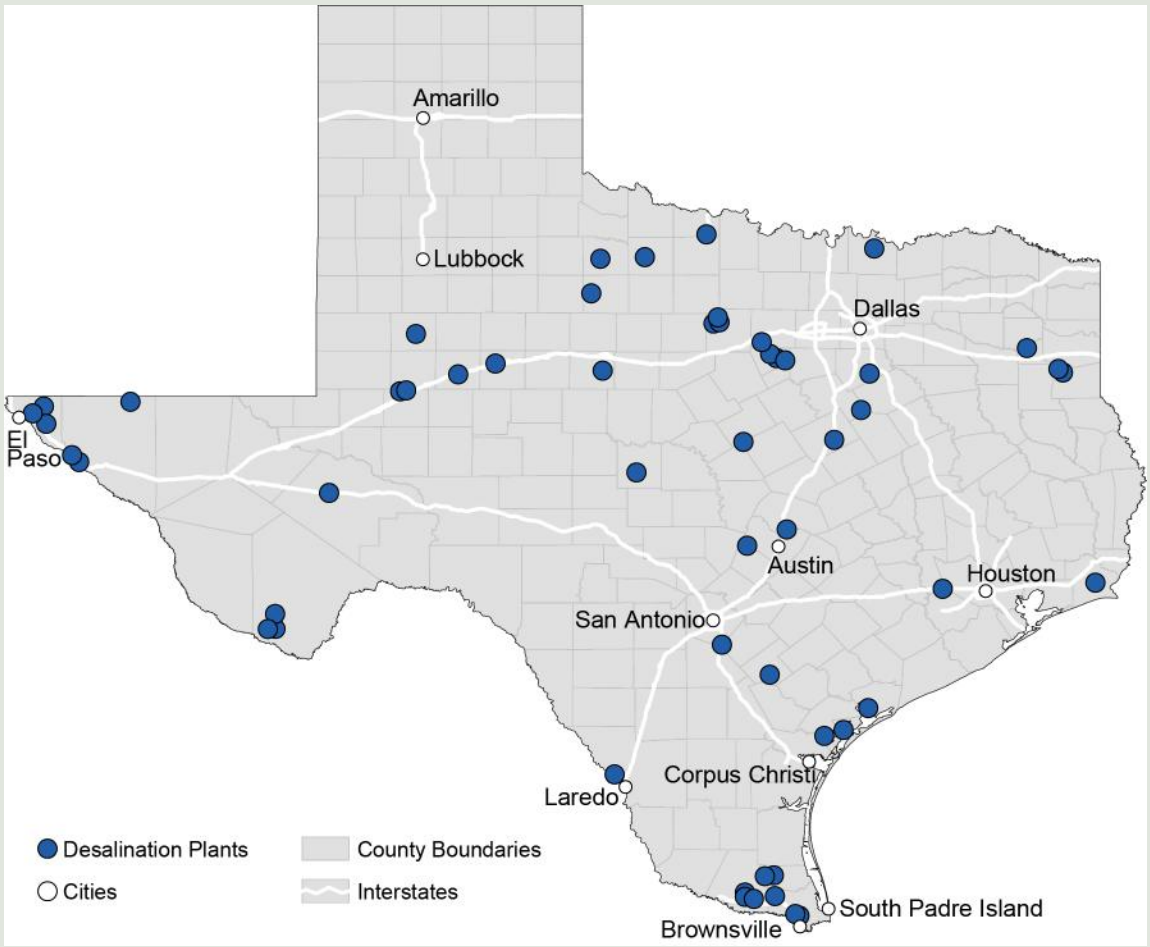


Figure 23.8: Desalination activities in Texas are an important contributor to the state's efforts to meet current and projected water needs for communities, industry, and agriculture. Source: adapted from Texas Water Development Board 2017.[110]

Key Message 3

Ecosystems and Ecosystem Services

Terrestrial and aquatic ecosystems are being directly and indirectly altered by climate change. Some species can adapt to extreme droughts, unprecedented floods, and wildfires from a changing climate, while others cannot, resulting in significant impacts to both services and people living in these ecosystems. Landscape-scale ecological services will increase the resilience of the most vulnerable species.

The Southern Great Plains encompasses diverse ecoregions (areas where ecosystems are generally similar) stretching from the High Plains to the Edwards Plateau and from the Tamaulipan Brushlands to the Gulf Coast Prairie.[118] The region is prone to periods of drought punctuated by heavy rainfall events, with evidence that these events are occurring more frequently.[10] These precipitation patterns influence water availability and aquatic habitats such as lakes, rivers, springs, and streams. Freshwater inflows from rivers flowing to coastal estuaries provide important nutrients and sediments while moderating salinities to create and maintain productive estuarine ecosystems.

Species Distribution and Habitats

Climate plays a key role in the distribution of species (Ch. 7: Ecosystems). Species' response to climate change is complex and variable.[119] As temperatures increase, the geographic distribution of some species tends to shift to areas with temperature ranges where a given species can survive. A notable species of concern in the region is the lesser prairie-chicken, which was listed as threatened under the U.S. Endangered Species Act in May 2014. Currently, the lesser prairie-chicken habitats include Kansas, Texas, and Oklahoma (as well as Colorado and New Mexico) with 70% of the population in Kansas.[120] At this time, it is not clear whether climate change will influence the lesser prairie-chicken in positive or negative ways.[121,122] Rising temperatures are also causing changes to growing seasons and migration patterns of birds and butterflies.[123] In Texas, white-wing doves, originally confined to the Lower Rio Grande valley, have been expanding northward [124] and are now common across Oklahoma. Other factors such as habitat loss also influence species distributions, making it difficult to pinpoint a single cause for these distribution changes.

While it is unclear how climate change will affect species directly, the effects of increased aridity will likely have negative impacts. In addition, ecosystem services—the materials and processes that ecosystems produce that benefit people—will also be affected.[123] In general, drought forces wildlife to travel farther to locate food, water, and shelter, which can deplete body condition going into winter or spring migration, when food sources are typically scarcer, making them more vulnerable to other stresses. The highly endangered Houston toad was negatively impacted during the 2011 drought and devastating wildfire in Bastrop County, Texas. Whooping crane numbers, which depend on sufficient freshwater inflows for a reliable food source (primarily blue crabs), were also reduced. In addition, a lack of freshwater can force whooping cranes to fly to uplands to drink, using more energy and exposing birds to more threats from predators and other mortality factors.

Aridification exacerbates stress in highly isolated habitats and fragmented lands, diminishing the ability for species to persist if they cannot move to better conditions. Migratory birds are better able to move to areas with better habitat conditions but could be in a weakened condition to do

so. Migratory waterfowl can also be negatively impacted by reductions in wetland habitat areas due to aridification. Loss of irrigated rice fields in Texas contributed to significant declines in wintering waterfowl along the Gulf Coast. The most significant decline was documented for snow geese, with a 71% decline for 2011–2014 as compared to the long-term average.[125] Playa lakes in the High Plains serve as important habitat for migrating waterfowl, but during the drought these wetlands were virtually nonexistent.

Plant community changes are also occurring, possibly due to climate change and other factors, and these changes in turn affect fish and wildlife. In the Southern Great Plains region, winters are warmer and spring is arriving earlier. Along the Texas coast, black mangroves, which are sensitive to cold, are expanding northward along the coast, and red mangroves, formerly not found in Texas, are now appearing there.[126] Warmer winters with fewer freezes are also conducive to pests and diseases. Woody shrubs invading prairie grasslands are favored by increases in concentrations of carbon dioxide (CO_2), changes in soil moisture cycles, fire suppression activities, and soil disturbances.[125] The 2011 drought produced a direct and indirect tree mortality rate of over 6%—many times the normal rate.[127]

Aquatic Ecosystems

Climate change impacts to aquatic ecosystems include higher water temperatures in lakes, wetlands, rivers, and estuaries that can result in lower dissolved oxygen, leading to more fish kills. Impacts to reservoirs include fluctuating lake levels, loss of habitat, loss of recreational access, increase in harmful algal blooms, and disconnectedness from upstream and downstream riverine habitats.[128] Localized declines in fish populations have been documented in rivers due to lack of water or water confined to increasingly narrow pools; in some cases, these declines prompted biologists to capture and relocate some endangered species to fish hatcheries.[129] Aridification (a gradual change to a drier climate) can have a number of negative impacts on freshwater mussel populations, including increased predation pressures, hypoxia (low oxygen conditions), increasing water temperature, and, ultimately, anoxia (no dissolved oxygen in water) or emersion (stranding the organism out of water and exposing it to air).

Coastal Areas, Bays, and Estuaries

The Texas coast, with 6.5 million people contributing over $37 billion to the region's economy, relies on its natural features, bays, and estuaries that serve as storm barriers to protect coastal infrastructure, and on its climate amenities to spur ecosystem services, such as fishing, ecotourism, and the ocean economy. These coastal ecosystems provide protection not only for people but also for 25% of the Nation's refining capacity, four crucial ports, much of the strategic petroleum reserves, and strategic military deployment and distribution installations. This protection was clearly on display with the recent impacts of Hurricane Harvey, where it has been estimated that natural coastal habitats protected about $2.4 billion worth of property in Texas and thousands of lives, with the suggestion that these habitats are potentially our first lines of defense.[130]

A rising sea level impacts more than 74% of Gulf-facing beaches in the upper Texas coast. The average rate of beach erosion is almost 10 feet per year.[131] Sea level rise means more frequent and longer-lasting flooding of marshes that eventually could be permanently flooded, becoming open water.[126,132] Higher tides and storm surges cause inundation of freshwater areas and beach erosion, leading to a potential decrease or loss of barrier islands and coastal habitats, including nesting habitats and submerged habitat such as seagrass beds affected by changes in water quality and changing water depths. A significant percentage of fishery species in the Gulf of Mexico are

dependent upon estuaries for some portion of their life cycle.[133]

The warming of bay waters on the Texas coast has been documented for at least 35 years. This mostly reflects warmer winters, not warmer summers. The increase in water temperature directly affects water quality, leading to the higher potential for low levels of dissolved oxygen, or hypoxia. Hypoxic events and harmful algal blooms have caused fish kills, leading to lower productivity and diversity of estuarine ecosystems.[126]

Freshwater inflows are critical to both aquatic ecosystems and wetlands in the Southern Great Plains. Both surface and groundwater depletion have led to dramatic changes of the aquatic and wetland communities in Kansas[134] that not only impact inland species but have a dramatic effect on coastal species relying on the freshwater inflow to ensure the integrity of the coastal ecosystem. Whooping crane and many other migratory species flying through this region during both spring and fall are impacted.[135] Climate change and human use have impacted these aquatic systems and wetlands and, ultimately, the vital flow of freshwater to the coastal marshes and estuaries.

Changes to freshwater inflows to estuaries lead to changes in salinity and inflows of nutrients and sediment, resulting in impacts to oysters and other sensitive estuarine species. In addition, harmful algal blooms have become more frequent, more intense, and more widespread.[123] Reduced freshwater inflows during 2011 led to record high salinities in Texas estuaries that contributed to a coast-wide "red tide" harmful algal bloom event. Red tides, a type of harmful algal bloom, most commonly occur during drought years, as the organism that causes red tide does not tolerate low salinity. Red tide blooms cause fish kills and contaminate oysters. In addition, oysters and other shellfish can accumulate red tide toxins in their tissues. People who eat oysters or other shellfish containing red tide toxins become seriously ill with neurotoxic shellfish poisoning. Once a red tide appears to be over, toxins can remain in the oysters for weeks to months. The 2011 bloom started in September and lasted into 2012. Fish mortality was estimated at 4.4 million. The commercial oyster season was closed and disaster declarations issued. The total economic loss was estimated at $7.5 million (dollar year not reported).[136]

Climate Winners and Losers (Gray Snapper and Southern Flounder)

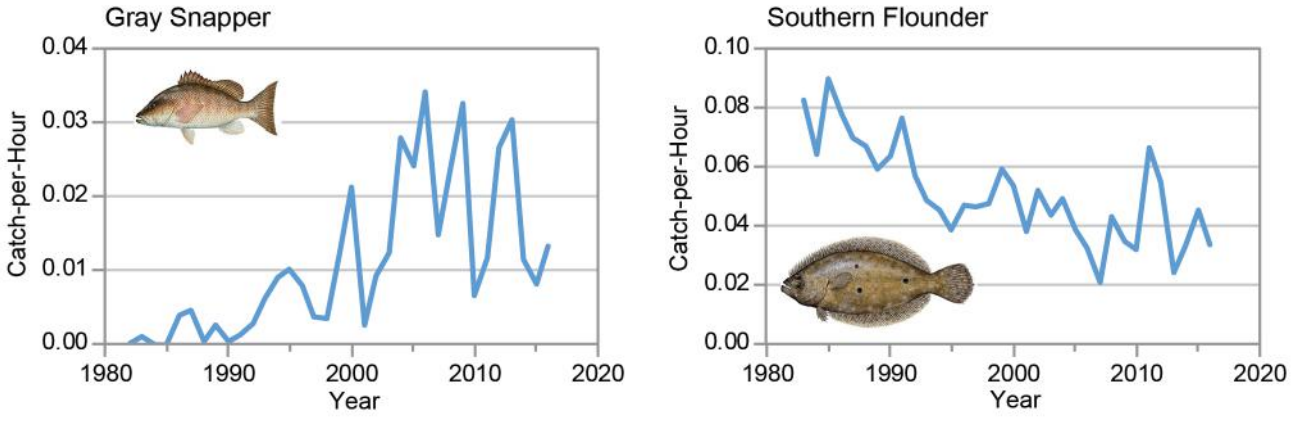


Figure 23.9: The graphs show trends in annual abundance of (left) gray snapper and (right) southern flounder as the number of fish caught per hour along the Gulf Coast of Texas between 1982 (snapper)/1983 (flounder) and 2016. As water temperatures increase along the Texas Gulf Coast, gray snapper are expanding northward along the Texas coast, while southern flounder, a popular sport fish, are becoming less abundant, impacting the recreational and commercial fishing industries. Source: Texas Parks and Wildlife Department.

Gray snapper have been ranging farther north since the 1990s; once found only in the lower Laguna Madre and off the extreme southern shore of Texas, they are now migrating northward along the upper Texas Coast. Conversely, flounder abundance has been declining due to the warmer winters,[137,138] since sex ratios (the number of males versus females) are influenced by temperature during flounder development and increases in temperature produce increasingly male-dominated sex ratios in southern flounder from Texas (See Figure 23.9).

Existing Options for Managing Risk

The National Fish, Wildlife, and Plants Climate Adaptation Strategy[123] was developed to provide natural resource managers and decision-makers the strategies and tools to address climate change impacts. The Strategy offers a guide for actions that can be taken in spite of remaining uncertainties over how climate change will impact living resources.

The Texas Edwards Aquifer Recovery Implementation Program Habitat Conservation Plan[78] balances water pumping and use of the aquifer with protection of eight federally listed threatened and endangered species that depend on San Marcos Springs and Comal Springs, two of the largest springs in the southwestern United States. These springs are the headwaters of the San Marcos and Comal Rivers and provide important water flow, especially during drought, to the Guadalupe River and Estuary.

Environmental flows—instream flows and freshwater inflows to bays and estuaries—are critical for sustaining aquatic ecosystems. In 2007, the Texas Legislature passed Senate Bill 3, which established a comprehensive, statewide process to protect environmental flows.[136] The process relies upon input from local stakeholder groups, composed of balanced interests ranging from agricultural water users to commercial anglers. The Texas Commission on Environmental Quality has adopted environmental flow standards intended to protect flow regimes that will help ensure healthy rivers, streams, and estuaries for Texas. The focus now is on adaptive management to refine standards, address research needs, and identify voluntary strategies to meet environmental flow standards.

The Texas Coastal Resiliency Master Plan[139] promotes coastal resilience, defined as the ability of coastal resources and coastal infrastructure to withstand natural or human-induced disturbances and quickly rebound from coastal hazards. This definition encompasses the two dimensions of resilience: 1) taking actions to eliminate or reduce significant adverse impacts from natural and human-induced disturbances, and 2) responding effectively in instances when such adverse impacts cannot be avoided. To keep pace with the dynamic Texas coastline, the Plan will be updated regularly to allow the state to continually assess changing coastal conditions and needs and to determine the most suitable way to implement the appropriate coastal protection solutions.

Key Message 4

Human Health

Health threats, including heat illness and diseases transmitted through food, water, and insects, will increase as temperature rises. Weather conditions supporting these health threats are projected to be of longer duration or occur at times of the year when these threats are not normally experienced. Extreme weather events with resultant physical injury and population displacement are also a threat. These threats are likely to increase in frequency and distribution and are likely to create significant economic burdens. Vulnerability and adaptation assessments, comprehensive response plans, seasonal health forecasts, and early warning systems can be useful adaptation strategies.

Extreme heat causes both direct and indirect impacts on human health and acts as a threat multiplier to the medically vulnerable. The increase in extreme heat due to climate change will exacerbate the medical issues associated with heat illness. More detail can be found in Chapter 14: Human Health. Notably, heat stress is strongly correlated with complications of lung disease, such as asthma and emphysema, as well as dehydration and injurious electrolyte abnormalities. It is estimated that each increase of approximately 1.8°F (1°C) in summer temperature increases the death rate for elders with chronic conditions by 2.8% to 4.0%.[140] During heat waves, concrete, blacktop, and the low ventilation capacity of urban "canyons" created by tall buildings can add 7°–12°F to the urban heat load.[141] The heat wave of 2011 exemplifies the human health and healthcare system impacts of extreme heat in the Southern Great Plains. The average temperature in Texas from June to August that year was 86.7°F (30.4°C), which broke all previous single-month records and was 5.2°F (2.9°C) higher than the long-term climatological average.[11] Studies demonstrated a 3.6% increase in emergency room visits and a 0.6% increase in deaths, with the largest effect on the elderly.[142,143] Within the Southern Great Plains, changes in extreme temperatures are projected to result in an additional 1,300 deaths per year under a higher scenario (RCP8.5) by the end of the century. Under a lower scenario (RCP4.5), more than half of these additional deaths could be avoided. Annual losses associated with extreme temperature-related mortality are estimated at $19 billion (2015 dollars) under RCP8.5 in 2090 and $9.4 billion (2015 dollars) under RCP4.5[144] (see the Scenario Products section of App. 3 for more on RCPs).

Rising temperatures and precipitation alter the habitats of vectors (mosquitoes, ticks, rodents, and fleas) that transmit a variety of human diseases. In the Southern Great Plains, hantavirus,[145] Rocky Mountain spotted fever,[146] leptospirosis,[147] and West Nile virus[148] are all currently endemic and could be impacted by climate change.[149,150] A warmer world will create newly hospitable habitats for tropical and subtropical insect vectors and the diseases they carry. Historically disease-free areas have been protected from becoming hazardous by cold environmental temperatures. That is, with extreme low temperatures of winter, insect (in particular, mosquito) populations are decimated. However, as the global average temperature increases, mosquitoes will thrive longer and reproduce more successfully at higher latitudes and altitudes. Tropical diseases, such as dengue virus,[151] chikungunya virus, and Zika virus are transmitted by *Aedes* mosquitoes, which are currently expanding their geographic range in the southern United States.[149] In southern Texas, sporadic, locally acquired outbreaks of dengue have been reported.[152] In 2005, there were 59 cases of dengue virus in southern Texas that met criteria for dengue hemorrhagic fever,[153] indicating that inhabitants were exposed to multiple variations of the virus, a condition necessary for the development of severe manifestations of dengue. In 2014, locally transmitted cases of chikungunya began to be reported in Texas.[154] Zika virus has also recently appeared in the region. In 2016, the Centers for Disease Control and Prevention (CDC) issued a travel warning for Cameron County, Texas, after the first case of local, person-to-person transmission of Zika was reported.[155] The ecology of vector-borne diseases is complex, and the future risk for proliferation and expansion of the ranges of these diseases is possible under future climate scenarios.[156,157] Along the southern Gulf Coast, stronger hurricanes will increase the likelihood of favorable ecologic niches for emerging infectious diseases that infect humans and animals.[158]

As water evaporates during periods of drought, the remaining water can have higher

concentrations of chemicals and solid particles, lower dissolved oxygen levels, and a higher density of germs that cause infectious diseases.[128] Drought conditions reduce the number of sources and overall quantity of water available to both human and animal users. Because these users are sharing a reduced supply, germ transmission and outbreaks of infectious disease become more likely. Waterborne diseases that have been linked to drought include amoebiasis, hepatitis A, salmonellosis, schistosomiasis, shigellosis, typhoid and paratyphoid fevers, infection with *E. coli*, cholera, and leptospirosis.[159,160,161,162] Skin infections, such as scabies and impetigo, and eye infections, including conjunctivitis, are also correlated with drought due to a lack of water available for personal hygiene.[163]

Droughts, floods, and higher temperatures will change the balance of ecosystems, allowing invasive species such as animal pests, plant weeds, and algae blooms to proliferate and harm existing agriculture.[164] Such conditions favor fungal species that can overwhelm crops and contaminate animal feedstocks. Additionally, increases in CO_2 are changing the nutritional composition of food crops.[165] Elevated CO_2 levels have been shown to reduce the protein composition of grains, tubers, rice, wheat, and barley.[166] Micronutrient contents are also affected by rising CO_2 levels, with atmospheric CO_2 concentrations of 550 parts per million being associated with reductions in zinc, iron, phosphorus, potassium, calcium, sulfur, magnesium, copper, and manganese across a wide range of crops.[167] Additionally, extreme temperatures and aridity pose health risks to outdoor agricultural workers.[168] Under a higher scenario (RCP8.5), the impact of temperature extremes at a national level are projected to result in the loss of two billion labor hours, equating to an estimated $160 billion (in 2015 dollars) in lost wages by the end of the century. The Southern Great Plains region is projected to experience higher-than-average impacts, with some communities projected to lose more than 6% in annual labor hours by the end of the century.[144]

State-level climate adaptation programs[169] have been developed throughout the Nation. For health, these include vulnerability and adaptation assessments, comprehensive response plans,[170,171] climate-proofing healthcare infrastructure, and implementing integrated surveillance of climate-sensitive infectious diseases. These efforts are outlined in more detail in Chapter 14: Human Health. Incorporating short-term to seasonal forecasts into public health activities can also provide assistance under a warming climate.[172] Although there is momentum to adopt adaptation strategies in the wake of Hurricane Harvey,[173] and adaptation strategies on a general scale (such as for drought) are in progress,[174] large-scale adaptation efforts in the region are lacking[175] and regional planners can learn from activities ongoing outside the region (Ch. 14: Human Health).

Key Message 5

Indigenous Peoples

Tribal and Indigenous communities are particularly vulnerable to climate change due to water resource constraints, extreme weather events, higher temperature, and other likely public health issues. Efforts to build community resilience can be hindered by economic, political, and infrastructure limitations, but traditional knowledge and intertribal organizations provide opportunities to adapt to the potential challenges of climate change.

Box 23.2: The Sun Dance Ceremony

Cheyenne tribal Chief Gordon Yellowman noted that excessive heat, invasive species, and drought threatened the Cheyenne Sun Dance ceremony. He related how natural materials are traditionally gathered for the ceremony by young men, called runners. Most significantly, willow branches for shade arbors were increasingly hard to find given the prolonged drought experienced in western Oklahoma. In areas where natural materials were gathered for the ceremony, invasive poison ivy was now present, with the vines choking out willow saplings and taking over. Many of the young men were poisoned to such an extent that they had to seek medical attention beyond traditional medicines in order to participate in the most important ceremony for the Cheyenne. In addition, an increase in the occurrences of heat illness at these ceremonies is preventing some tribal members from participating in or completing the ceremony.

Figure 23.10: Chief Gordon Yellowman is shown here representing the Cheyenne Tribe at a traditional speaking engagement. Photo courtesy of Gordon L. Yellowman, Sr.

The 45 federally recognized tribes (48 if state-recognized tribal nations are included) located in the Southern Great Plains show considerable economic, social, cultural, and linguistic/language diversity.[176,177,178] The 4 tribes of Kansas (59,130 people), 39 tribes of Oklahoma (482,760 people), including 1 state-recognized tribe, and 5 tribes of Texas (6,210 people), including 2 state-recognized tribes, experience the same climate change impacts as the rest of the Nation.[14] However, these sovereign nations within the United States are faced with infrastructure (social and physical), economic, political, and cultural challenges, as well as unique opportunities, in their response to climate change impacts (Ch. 15: Tribes).

Climate Change Threats to Tribal Cultural Traditions and Community Resilience

No climate change impacts are as significant to the tribes and Indigenous peoples of the Southern Great Plains as those that threaten the ability to procure food, water, shelter, and preserve ancient cultural activities.[179,180,181] Given the ancient symbiotic relationship between environment and culture that shapes tribal identities and life-way practices, climate-induced changes to the seasons, landscapes, and ecosystems pose an existential threat to tribal cultural traditions and community resilience.[182,183,184] For example, climate change, including the impacts of excessive heat, drought, and the disappearance of native species, is already disrupting ceremonial cycles in Oklahoma.[185] However, many climate change adaptation initiatives and strategies are being developed by tribes throughout the United States. Specific examples in the Southern Great Plains can be found in Figure 15.1 in Chapter 15: Tribes.

Physical and Organizational Infrastructure

The region's tribes and Indigenous peoples vary greatly in size, from small nations with fewer than 1,000 enrolled members to larger nations with over 50,000 enrolled members; the largest of the tribes is the Cherokee Nation with more than 317,000 enrolled members.[186] The smaller nations, given their population size and respective size of government, often struggle to exercise their sovereignty to respond to climate change due to a lack of organizational and physical infrastructure.[187,188] The social organizational infrastructure needed to adapt to climate change impacts like extreme weather events, rising temperatures, shifting seasons, invasive species, air and water quality issues, and a host of health impacts

is often lacking or underdeveloped in small tribal nations. Consequently, the smaller tribes depend largely on the services, grant programs, and technology transfer capabilities of the Bureau of Indian Affairs and other Federal Government departments, agencies, and bureaus to assist in their climate adaptation efforts. There are exceptions—larger and wealthier tribal nations, such as the Chickasaw Nation, Citizen Band Potawatomi, and Muscogee (Creek) Nation, can develop and shape, to a much larger extent, their own climate adaptation strategies.[169]

Lack of physical infrastructure, tied directly to limited economic resources and power, poses a substantial obstacle to climate change adaptation for the tribes of the region. While cities and other governmental jurisdictions make plans to build resilient physical infrastructure by using bonds, public–private partnerships, and taxes and tax instruments, only a handful of tribal nations have the ability to use these tools for climate adaptation. Most tribes and Indigenous peoples remain dependent on underfunded federal programs and grants for building and construction activities to improve the resilience of their infrastructure in the face of climate change threats. Many larger and wealthier tribes have modeled construction and design of homes and large commercial building best practices on "green" or resilient net-zero carbon footprint designs. Increasing activity in community gardens, food recovery, recycling, water conservation, land-use planning, and investment in climate-resilient community design all signal opportunities for tribal nations to leapfrog significant obstacles other city, county, and state governments face when dealing with the costs of existing physical infrastructure that often make climate change adaptation difficult and incremental.

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Whooping cranes: Jon Noll/U.S. Department of Agriculture.

Traceable Accounts

Process Description

The initial Southern Great Plains author team was selected such that expertise from each of the states' officially recognized climate offices in the region (Kansas, Oklahoma, and Texas) were included. The offices of the state climatologist in Kansas, Oklahoma, and Texas are each members of the American Association of State Climatologists, which is the recognized professional scientific organization for climate expertise at the state level.

One representative from each of several regional hubs of national and regional climate expertise was included on the author team. These regional hubs include the U.S. Department of Agriculture's Southern Plains Climate Hub (El Reno, Oklahoma), the U.S. Department of the Interior's South Central Climate Adaptation Science Center (Norman, Oklahoma), and the National Oceanic and Atmospheric Administration's Regional Integrated Sciences and Assessments Southern Climate Impacts Planning Program (Norman, Oklahoma).

After assessing the areas of expertise of the six authors selected from the state and regional centers, a gap analysis was conducted to prioritize areas of expertise that were missing. Due to the importance of the sovereign tribal nations to the Southern Great Plains, an accomplished scholar with expertise in Indigenous knowledge on the environment and climate change was selected from the premier tribal university in the United States, Haskell Indian Nations University in Lawrence, Kansas. An individual from the Environmental Science Institute at the University of Texas at Austin was selected to bring expertise on the complex intersection of coupled atmosphere–land–ocean systems, climate, and humans (population and urbanization). Expertise in the electric utility industry was gained through the Oklahoma Association of Electric Cooperatives by an individual with a long history of working with rural and urban populations and with researchers and forecasters in weather and climate.

The author group decided to allow Southern Great Plains stakeholders to drive additional priorities. On March 2, 2017, the Fourth National Climate Assessment (NCA4) Southern Great Plains chapter team held a Regional Engagement Workshop at the National Weather Center in Norman, Oklahoma, with a satellite location in Austin, Texas, that allowed a number of stakeholders to participate virtually. The objective of the workshop was to gather input from a diverse array of stakeholders throughout the Southern Great Plains to help inform the writing and development of the report and to raise awareness of the process and timeline for NCA4. Stakeholders from meteorology, climatology, tribes, agriculture, electric utilities, water resources, Bureau of Land Management, ecosystems, landscape cooperatives, and transportation from Kansas, Oklahoma, and Texas were represented. The productive dialog at this workshop identified important gaps in environmental economics, ecosystems, and health. Scientists working at the cutting edge of research in these three areas were selected: an ecosystems expert from the Texas Parks and Wildlife Department, an environmental economist from the department of Geography and Environmental Sustainability at the University of Oklahoma, and health experts from the University of Colorado School of Medicine and the Aspen Global Change Institute.

This diverse collection of medical doctors, academics, researchers, scientists, and practitioners from both federal and state agencies gives the Southern Great Plains chapter a wealth of expertise across the many ways in which climate change will affect people in the region.

Key Message 1

Food, Energy, and Water Resources

Quality of life in the region will be compromised as increasing population, the migration of individuals from rural to urban locations, and a changing climate redistribute demand at the intersection of food consumption, energy production, and water resources (*likely, high confidence*). A growing number of adaptation strategies, improved climate services, and early warning decision support systems will more effectively manage the complex regional, national, and transnational issues associated with food, energy, and water (*likely, high confidence*).

Description of evidence base

The connection between food, water, and energy also creates great challenges in the management and distribution of resources. People need food, energy, and water, yet all sectors pull from each other and allocation is a challenge. There are many studies focused on the competitive nature revolving around these resources and the demand by people.[41,59,60,61,62,63,64,65] The management and application of these issues are social in context and require significant communication and collaboration to resolve. As demands for these resources become more acute, development of collaborative processes to ensure integrated use and allocation may be required.

Major uncertainties

Research into the intersection of food, energy, and water is in its early stages and historically tends to examine only one or two components.[59,60,61,62,63,64,65] It is clear that tradeoffs and cascading complexities exist between sectors, and changes in one sector are likely to propagate through the entire system. There are significant gaps in the scientific understanding regarding the role that climate change will play as a disruptive force and a threat to food, energy, and water security.[60,63,66,67,68] It is likely, and with significant certainty, that the competition for and use of the resources by people will continue; however, the likelihood of developing a means to manage this situation is challenging. The added complexities of people and cultures, a rapidly growing population (see next section), and the diminishing availability of resources (water especially) in this region will be an important future research topic.

Description of confidence and likelihood

The Southern Great Plains will continue to grow rapidly and with high probability of significant competition. Water is the major concern, and political inability to develop a system to allocate water in an equitable manner will continue to build this competitive and contentious issue among all users—energy, food, and water. Quality of life in the region will be compromised as population increases. At least 60% of the region's population is clustered around urban centers currently, but these population centers are experiencing growth that far exceeds that of rural communities. The remaining population is distributed across vast areas of rural land.[14,30,31,32,33] Therefore, the migration of individuals from rural to urban locations, combined with climate change, redistributes

demand at the intersection of food consumption, energy production, and water resources. (*Likely, High confidence*)

A growing number of adaptation strategies, improved climate services, and early warning decision support systems will more effectively manage the complex regional, national, and transnational issues associated with food, energy, and water. Since a changing climate has significant negative impacts on agriculture in the United States and causes substantial economic costs,[38] the effects of drought and other occurrences of extreme weather outside the region will also affect the food–energy–water interconnections within the region. (*Likely, High confidence*)

Key Message 2

Infrastructure

The built environment is vulnerable to increasing temperature, extreme precipitation, and continued sea level rise, particularly as infrastructure ages and populations shift to urban centers (*likely, high confidence*). Along the Texas Gulf Coast, relative sea level rise of twice the global average will put coastal infrastructure at risk (*likely, medium confidence*). Regional adaptation efforts that harden or relocate critical infrastructure will reduce the risk of climate change impacts.

Description of evidence base

The existing infrastructure and projected models for growth are well established and documented. Demographic and population projections are available from state demographers and are typically included in Long-Term Transportation Plans available from state departments of transportation. Additionally, the present-day infrastructure challenges have been examined in depth by the American Society for Civil Engineers (ASCE), which publishes an Infrastructure Report Card for the Nation and for each state (www.infrastructurereportcard.org).[189] For the Southern Great Plains states, one of the pressing concerns is meeting the funding challenges necessary to maintain critical infrastructure, as well as anticipating future revenue streams, which themselves depend on population and its distribution, and state and federal funding. The ASCE, as well as all state transportation plans in the Southern Great Plains, does not consider future climate projections, and the information contained generally does not explicitly mention climate-related stressors. However, the impacts of climate change have become an issue of concern for agencies such as the Department of Transportation (DOT) and Federal Highways Administration (FHWA), which have in recent years funded projects evaluating the potential impacts of climate change on infrastructure and transportation and possible adaptation strategies. Since 2010, the FHWA has sponsored a series of pilot studies in resilience for municipalities and states across the Nation.[190] Two of these studies took place in Texas, in Dallas and Tarrant Counties and in the City of Austin. These reports provide some of the most comprehensive examples of integrating climate data into assessments of infrastructure vulnerability in the region to date. The potential impacts of temperature and precipitation extremes on transportation and infrastructure were based in part on known vulnerabilities as shown by these aforementioned reports and the larger repository of information and resources supplied by the FHWA.

Estimates of relative sea level rise (SLR) in Texas in the historical period are available from NCA4 Volume I: *Climate Science Special Report*,[24] Runkle et al. (2017),[25] Sweet et al. (2017).[191] Relative SLR along the Texas coastline is some of the highest in the Nation; coupled with its population and critical energy infrastructure, this region has some noteworthy vulnerabilities to SLR. Projections of SLR remain uncertain and depend to some extent on whether the current rates of relative SLR are maintained, in addition to the magnitude and rate of greenhouse gas emissions. Sweet et al. (2017)[191] probabilistically evaluate a number of SLR scenarios, typically noting that the Texas coast SLR is higher than the global mean. The values mentioned in the main text are global mean values obtained from USGCRP (2017)[24] and from the range quoted by Runkle et al. (2017).[25]

Major uncertainties

In the Southern Great Plains there remains uncertainty over the direction of change of average precipitation, although models generally project increases in very heavy precipitation.[1] The expectation of an increase in the frequency of events such as the 100-year storm is uncertain due to the spread of model projections of extreme precipitation and the need to use additional statistical modeling in order to obtain the return period estimates.

There are limited studies that attempt to directly link weather and climate extremes and their impacts to infrastructure. While it is appreciated that infrastructure exposed to adverse conditions will lead to deterioration, studies on specific cause–effect chain of events in these cases are limited (e.g., Winguth et al. 2015[192]).The results are more evident in the case of catastrophic failures associated with floods, for example, but even in those cases, antecedent conditions related to the age, condition, and/or construction quality of infrastructure will affect its resilience (Ch. 12: Transportation).

Description of confidence and likelihood

There is *very high confidence* that extreme heat will increase in frequency and intensity. There is *medium confidence* in an increased frequency of flooding and *high confidence* in the increased frequency of drought. There is *high confidence* of sea level rise of at least 4 feet by 2100 along the Texas coastline if greenhouse gas emissions are not reduced. On the implications for infrastructure, there is *high confidence* that weather-related damage will increase due to inland weather-related hazards. Along the coastline, there is *very high confidence* that infrastructure will be impacted by sea level rise and storm surge.

Key Message 3

Ecosystems and Ecosystem Services

Terrestrial and aquatic ecosystems are being directly and indirectly altered by climate change (*likely, high confidence*). Some species can adapt to extreme droughts, unprecedented floods, and wildfires from a changing climate, while others cannot, resulting in significant impacts to both services and people living in these ecosystems (*likely, high confidence*). Landscape-scale ecological services will increase the resilience of the most vulnerable species.

Description of evidence base

This Key Message was developed through technical discussions developed within science teams and collaborators of the Gulf Coast and Great Plains Landscape Conservation Cooperatives. Species' response to climate change is complex and variable;[119] this complexity necessitates a multifaceted review of the projected impacts of climate change. In addition, ecosystem services also require assessment, given the impact of climate change on their ability to deliver materials and processes that benefit people.[123]

The following relevant areas of evidence regarding climate change impacts on ecosystems in the Southern Great Plains were therefore considered: species, aquatic ecosystems, coastal bays and estuaries, and risk management. It is unclear how climate change will affect species directly, but the effects of increased aridity will likely have negative impacts (e.g., NFWPCAP 2012[123]). Species migration (e.g., Schmandt 2011[126]) and mortality (e.g., Moore et al 2016[127]) will increase in response to climate change. Climate change impacts to aquatic ecosystems include higher water temperatures in lakes, wetlands, rivers, and estuaries, while impacts to reservoirs include fluctuating lake levels, loss of habitat, loss of recreational access, increase in harmful algal blooms, and disconnectedness from upstream and downstream riverine habitat.[129] Sea level rise will impact coastal bays and estuaries via more frequent and longer-lasting flooding of marshes,[126,132] while higher tides and storm surges cause inundation of freshwater areas and beach erosion, leading to a potential decrease or loss of barrier islands and coastal habitats, including nesting habitats and submerged habitats such as seagrass beds affected by changes in water quality and changing water depths.[133] Other ecosystem-centered impacts include surface and groundwater depletion (e.g., Perkin et al. 2017[134]) and changes in migratory species pathways.[135]

Major uncertainties

Ecosystems and the species that exist in these ecosystems have experienced a rapid decline in many "common species" as well as certain rare species.[123,137,138] Increases in many nonnative species have led to both concern and opportunity. Continued habitat and population shifts and the impact of interactions between people, other resources, and available habitat stressors are vague. Indirect impacts to livestock and agricultural systems are also unknown. The likelihood of animal and plant diseases and parasites impacting commercial production and the interaction with wild species is anticipated but uncertain.

Description of confidence and likelihood

There is *high confidence* that rising temperatures and increases in flooding, runoff events, and aridity will *likely* lead to changes in the aquatic and terrestrial habitats supporting many regional species. Flooding has changed the complexity of many riparian habitats. Increases already seen in extreme drought occurrence have caused downturns in the fish- and wildlife-related industries, with losses in traditional fish (crab and oysters) and wildlife species (waterfowl) important for both recreational and commercial purposes.

In contrast, habitat created by invasive species due to climate change has improved populations of other species including fungi. The expanded stress due to a rapidly growing population in this region increases the likelihood (*high confidence*) of negative natural resource and ecosystems outcomes in the future.

Key Message 4

Human Health

Health threats, including heat illness and diseases transmitted through food, water, and insects, will increase as temperature rises (*very likely, high confidence*). Weather conditions supporting these health threats are projected to be of longer duration or occur at times of the year when these threats are not normally experienced (*likely, medium confidence*). Extreme weather events with resultant physical injury and population displacement are also a threat (*likely, high confidence*). These threats are likely to increase in frequency and distribution and are likely to create significant economic burdens (*likely, high confidence*). Vulnerability and adaptation assessments, comprehensive response plans, seasonal health forecasts, and early warning systems can be useful adaptation strategies.

Description of evidence base

This Key Message was developed in close coordination with the Human Health (Ch. 14) author team and incorporated applicable inputs from the U.S. Climate and Health Assessment.[168] Multiple lines of evidence demonstrate statistically significant associations between temperature, precipitation, and other climatologic variables with adverse health outcomes, including heat-related illness, respiratory disease, malnutrition, and vector-borne disease.[168] Regionally specific examples of these well-documented impacts were identified through literature reviews conducted to identify regionally specific studies of these impacts.

There is strong evidence that increasing average temperatures as well as increasing frequency, duration, and intensity of extreme heat events will occur in the Southern Great Plains by the middle and end of this century, with higher CO_2 emissions leading to greater and faster temperature increases.[80] Extreme temperatures are shown with *high confidence* to have substantial effects on morbidity and mortality [142,143,168] by causing heat-related illness and by increasing the risk of cardiovascular events, cerebrovascular events, respiratory disease, renal failure, and metabolic derangements.[193,194] In addition to impacting health and well-being, extreme heat is likely to lead to a significant economic impact through an increase in healthcare costs, premature mortality, and lost labor.[195] Within the Southern Great Plains, climate change is likely to exacerbate aridity due to drying of soils and increased evapotranspiration caused by higher temperatures.[80] Such aridity is likely to negatively impact the agricultural sector, contributing to food insecurity and increased pesticide use.[165] Extreme temperatures are projected to further impair food production in the region by significantly impacting the health and work capacity of outdoor workers.[144] Additionally, shifting temperature and precipitation patterns are making habitats more suitable for disease-carrying vectors to move northward towards the Southern Great Plains region.[149,150] In southern Texas, sporadic, locally acquired outbreaks of dengue, chikungunya, and Zika have been reported.[152,154,155] These diseases are transmitted by the *Aedes agypti* mosquitoes, which are currently expanding their geographic range into the Southern Great Plains region.[149,196]

Climate change is expected (with *medium to high confidence*) to increase the frequency of extreme rainfall and hurricanes, although impacts in the Southern Great Plains remain difficult to quantify.[2] The Gulf Coast of Texas in particular has experienced several record-breaking floods and tropical

cyclones in recent years, including Hurricane Harvey. Hurricanes and resultant flooding result in significant health impacts, including deaths from drowning and trauma, critical shortages of essential medications, critical healthcare system power shortages, and forced patient evacuations.[9] Such events strain healthcare resources not only within regions of direct hurricane impact but also within the entire region due to displacement of patient populations.[8]

Major uncertainties

The ability to quantitatively predict specific health outcomes associated with projected changes in climate is limited by long-term public health data as well as meteorological data. While assessments consistently indicate that climate change will have direct and indirect impacts on human health (*high confidence*), quantifying specific health metrics, such as incidence and community level prevalence, remains difficult. The uncertainty develops when there are many connected actions that influence health outcomes. For example, the future impact of climate change on human health is likely to be reduced by adaptation measures that take place on local and national scales. Additionally, the role of non-climate factors, including land use, socioeconomics, and population characteristics (such as immigration), as well as health sector policies and practices, will affect local and regional health impacts. The magnitude of impact of these variables on health at local and regional scales is difficult to predict. The estimation of future economic impacts is limited by difficulties in estimating the true cost of healthcare delivery and additionally only partially captures the actual impacts on health and livelihood of individuals and communities. Thus, existing projections likely underestimate the entirety of the economic impact.

Description of confidence and likelihood

There is *very high confidence* that rising temperatures and changes in precipitation leading to flooding, runoff events, and aridity will *likely* lead to negative impacts on human health in the Southern Great Plains. There is *high confidence* that certain populations, such as very young and old and socioeconomically disadvantaged individuals, will *likely* be disproportionately affected.

Key Message 5

Indigenous Peoples

Tribal and Indigenous communities are particularly vulnerable to climate change due to water resource constraints, extreme weather events, higher temperature, and other likely public health issues (*likely, high confidence*). Efforts to build community resilience can be hindered by economic, political, and infrastructure limitations (*likely, high confidence*), but traditional knowledge and intertribal organizations provide opportunities to adapt to the potential challenges of climate change.

Description of evidence base

This Key Message was developed through dialog and discussions among Indigenous communities and within the social sciences discipline. While Indigenous communities vary in size from smaller nations to large well-formed governments, all are in need of communication about the realities of climate change.[14] Climate change threatens the ability of tribes and Indigenous peoples to procure food, water, and shelter and to preserve ancient cultural activities.[179,180,181] The impacts of excessive

heat, drought, and the disappearance of native species are already disrupting ceremonial cycles in Oklahoma.[185] There is strong evidence that because of the unique nature of the Indigenous communities, including previous and ongoing experiences of the communities, the collective economic and political power for enacting efficient and effective climate adaptation responses could be limited at best.[182,183,184] There is a consensus among the nations that impacts of climate change will be a direct threat to the symbiotic connection between environment and the tribal traditions connecting the people with the land.

Major uncertainties

There is a great deal of uncertainty regarding how tribal communities will integrate climate change into their cultures, given the variable size of these communities and the challenges of connecting and communicating with clarity among them. It is likely that adaptation strategies will vary greatly as knowledge and communication might not be widely supported within all nations.[169,187,188] Due to disproportionate rates of poverty and access to information and collaborative support, some communities could suffer more than others; however, the degree and the impacts of such are unclear.

Description of confidence and likelihood

There is *high confidence* that extreme events and long-term climate shifts will lead to changes in tribal and Indigenous communities in the Southern Great Plains. Environmental connections will be direct, but the degree of those connections is uncertain and shifts in climate system will impact each nation differently. How changes will be perceived and managed and what steps are taken to adapt are uncertain; thus, there is *low confidence* that adaptation will be a successful mechanism among all tribal and Indigenous peoples.

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24 Northwest

Four Lakes basin in White Cloud Peaks, Sawtooth National Forest, Idaho

Key Message 1

Natural Resource Economy

Climate change is already affecting the Northwest's diverse natural resources, which support sustainable livelihoods; provide a robust foundation for rural, tribal, and Indigenous communities; and strengthen local economies. Climate change is expected to continue affecting the natural resource sector, but the economic consequences will depend on future market dynamics, management actions, and adaptation efforts. Proactive management can increase the resilience of many natural resources and their associated economies.

Key Message 2

Natural World and Cultural Heritage

Climate change and extreme events are already endangering the well-being of a wide range of wildlife, fish, and plants, which are intimately tied to tribal subsistence culture and popular outdoor recreation activities. Climate change is projected to continue to have adverse impacts on the regional environment, with implications for the values, identity, heritage, cultures, and quality of life of the region's diverse population. Adaptation and informed management, especially culturally appropriate strategies, will likely increase the resilience of the region's natural capital.

Key Message 3

Infrastructure

Existing water, transportation, and energy infrastructure already face challenges from flooding, landslides, drought, wildfire, and heat waves. Climate change is projected to increase the risks from many of these extreme events, potentially compromising the reliability of water supplies, hydropower, and transportation across the region. Isolated communities and those with systems that lack redundancy are the most vulnerable. Adaptation strategies that address more than one sector, or are coupled with social and environmental co-benefits, can increase resilience.

Key Message 4

Health

Organizations and volunteers that make up the Northwest's social safety net are already stretched thin with current demands. Healthcare and social systems will likely be further challenged with the increasing frequency of acute events, or when cascading events occur. In addition to an increased likelihood of hazards and epidemics, disruptions in local economies and food systems are projected to result in more chronic health risks. The potential health co-benefits of future climate mitigation investments could help to counterbalance these risks.

Key Message 5

Frontline Communities

Communities on the front lines of climate change experience the first, and often the worst, effects. Frontline communities in the Northwest include tribes and Indigenous peoples, those most dependent on natural resources for their livelihoods, and the economically disadvantaged. These communities generally prioritize basic needs, such as shelter, food, and transportation; frequently lack economic and political capital; and have fewer resources to prepare for and cope with climate disruptions. The social and cultural cohesion inherent in many of these communities provides a foundation for building community capacity and increasing resilience.

Executive Summary

Residents of the Northwest list the inherent qualities of the natural environment among the top reasons to live in the region. The region is known for clean air, abundant water, low-cost hydroelectric power, vast forests, extensive farmlands, and outdoor recreation that includes hiking, boating, fishing, hunting, and skiing. Climate change, including gradual changes to the climate and in extreme climatic events, is already affecting these valued aspects of the region, including the natural resource sector, cultural identity and quality of life, built infrastructure systems, and the health of Northwest residents. The communities on the front lines of climate change—tribes and Indigenous peoples, those most dependent on natural resources for their livelihoods, and the economically disadvantaged—are experiencing the first, and often the worst, effects.

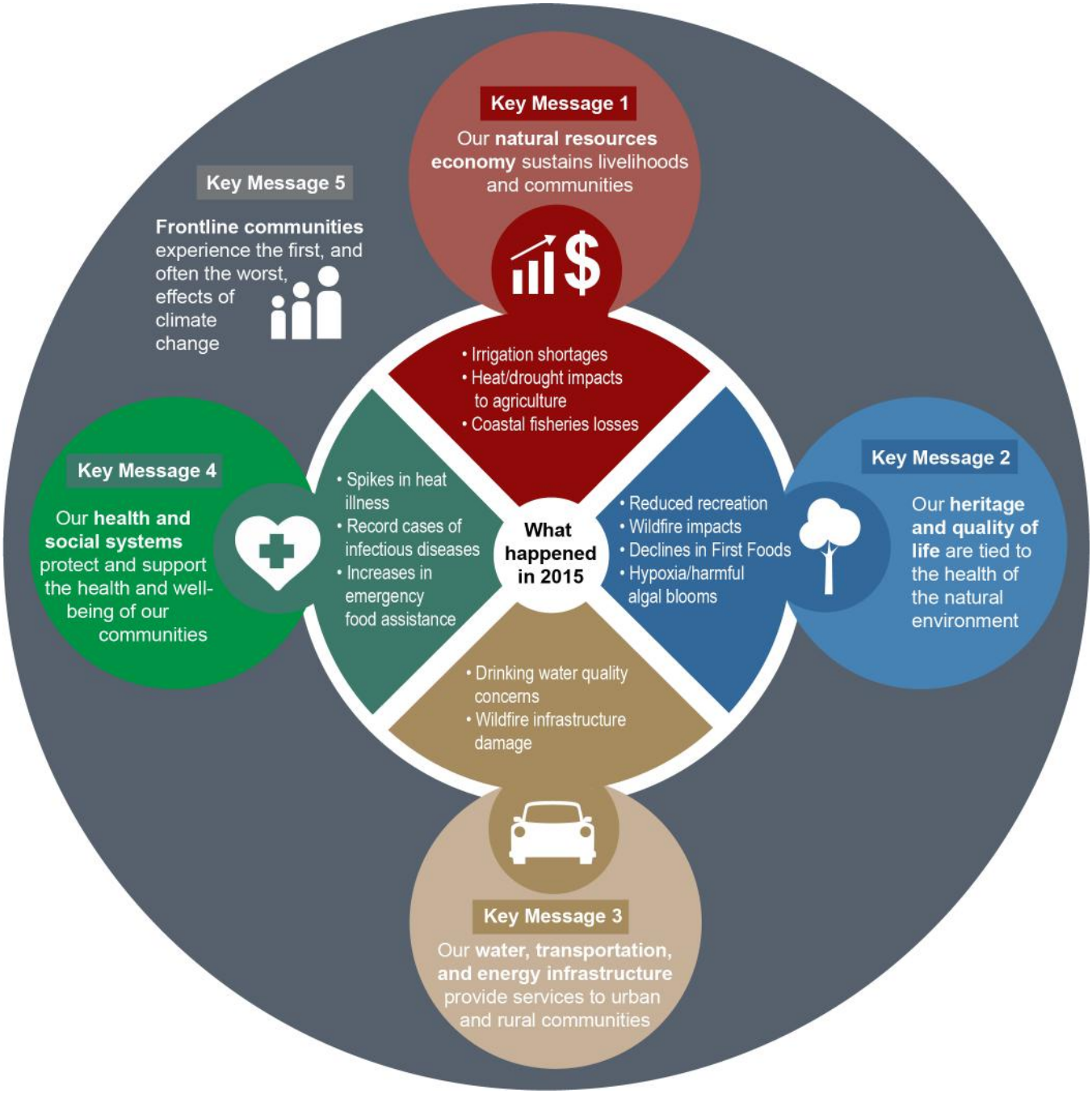
In the Third National Climate Assessment, the Key Messages for the Northwest focused on projected climate impacts to the region.[1] These impacts, many of which are now better understood in the scientific literature, remain the primary climate concerns over the coming decades. In this updated assessment, the Key Messages explore how climate change could affect the interrelationships between the environment and the people of the Northwest. The extreme weather events of 2015 provide

an excellent opportunity to explore projected changes in baseline climate conditions for the Northwest. The vast array of climate impacts that occurred over this record-breaking warm and dry year, coupled with the impacts of a multiyear drought, provide an enlightening glimpse into what may be more commonplace under a warmer future climate. Record-low snowpack led to water scarcity and large wildfires that negatively affected farmers, hydropower, drinking water, air quality, salmon, and recreation. Warmer than normal ocean temperatures led to shifts in the marine ecosystem, challenges for salmon, and a large harmful algal bloom that adversely affected the region's fisheries and shellfish harvests.

Strong climate variability is likely to persist for the Northwest, owing in part to the year-to-year and decade-to-decade climate variability associated with the Pacific Ocean. Periods of prolonged drought are projected to be interspersed with years featuring heavy rainfall driven by powerful atmospheric rivers and strong El Niño winters associated with storm surge, large waves, and coastal erosion. Continued changes in the ocean environment, such as warmer waters, altered chemistry, sea level rise, and shifts in the marine ecosystems are also expected. These changes would affect the Northwest's natural resource economy, cultural heritage, built infrastructure, and recreation as well as the health and welfare of Northwest residents.

The Northwest has an abundance of examples and case studies that highlight climate adaptation in progress and in practice—including creating resilient agro-ecosystems that reduce climate-related risks while meeting economic, conservation, and adaptation goals; using "green" or hybrid "green and gray" infrastructure solutions that combine nature-based solutions with more traditional engineering approaches; and building social cohesion and strengthening social networks in frontline communities to assist in meeting basic needs while also increasing resilience to future climate stressors. Many of the case studies in this chapter demonstrate the importance of co-producing adaptation efforts with scientists, resource managers, communities, and decision-makers as the region prepares for climate change impacts across multiple sectors and resources.

Climate Change Will Impact Key Aspects of Life in the Northwest



The climate-related events of 2015 provide a glimpse into the Northwest's future, because the kinds of extreme events that affected the Northwest in 2015 are projected to become more common. The climate impacts that occurred during this record-breaking warm and dry year highlight the close interrelationships between the climate, the natural and built environment, and the health and well-being of the Northwest's residents. *From Figure 24.2 (Source: USGCRP).*

Background

Residents of the Northwest list the inherent qualities of the natural environment among the top reasons to live in the region. The Northwest is known for clean air, abundant water, low-cost hydroelectric power, vast forests, extensive farmlands, and an array of outdoor recreation that includes hiking, boating, fishing, hunting, and skiing. Warming and related changes in climate are already affecting aspects of the Northwest's identity such as its natural resource economy and its cultural heritage that is deeply embedded within the natural environment. The built systems that support Northwest residents and the health of residents themselves are also already experiencing the effects of climate change. The communities on the front lines of climate change experience the first, and often the worst, effects. Frontline communities in the Northwest include tribes and Indigenous peoples, the economically disadvantaged, and those most dependent on natural resources for their livelihoods.

The region has warmed substantially—nearly 2°F since 1900—and this warming is partially attributable to human-caused emissions of greenhouse gases.[2,3,4] Warmer winters have led to reductions in the mountain snowpack[5,6] that historically blanketed the region's mountains, increasing wildfire risk (Ch. 6: Forests, KM 1)[7,8] and speeding the usually slow release of water for communities, agriculture, rivers, and soils. In 2015, record winter warmth led to record-low snowpack in much of the Northwest's mountains as winter precipitation fell as rain instead of snow,[9] resulting in drought, water scarcity, and large wildfires that negatively affected farmers, hydropower, drinking water, salmon, and recreation. In addition, warmer ocean temperatures led to shifts in the marine ecosystem, challenges for salmon, and a large harmful algal bloom.[10] The extreme

Detroit Lake Reservoir During Multiyear Drought

Figure 24.1: Detroit Lake Reservoir in Oregon at record-low levels in 2015. Photo credit: Dave Reinert, Oregon State University.

climate-related events of 2015 have prompted Northwest states, cities, tribes, and others to increase and prioritize climate preparedness efforts, as evidenced by the presentations at the 6th and 7th annual Northwest Climate Conference (http://pnwclimateconference.org/CdA2015/ and http://pnwclimateconference.org/Stevenson2016/).

Climate change affects the interrelationships between the environment and the people of the Northwest, and extreme climate events, such as those that occurred during 2015, provide a preview of what may be more commonplace under a warmer future climate (Figure 24.2). The Northwest is projected to continue to warm during all seasons under all future scenarios, although the rate of warming depends on current and future emissions.[11] The warming trend is projected to be accentuated in certain mountain areas in late winter and spring,[9] further exacerbating snowpack loss and increasing the risk for insect infestations and wildfires.[12] In central Idaho and eastern Oregon and Washington, vast mountain areas have already been transformed by mountain pine beetle infestations, wildfires, or both, but the western Cascades and coastal mountain ranges have less experience with these growing threats.[13]

Climate Change Will Impact Key Aspects of Life in the Northwest

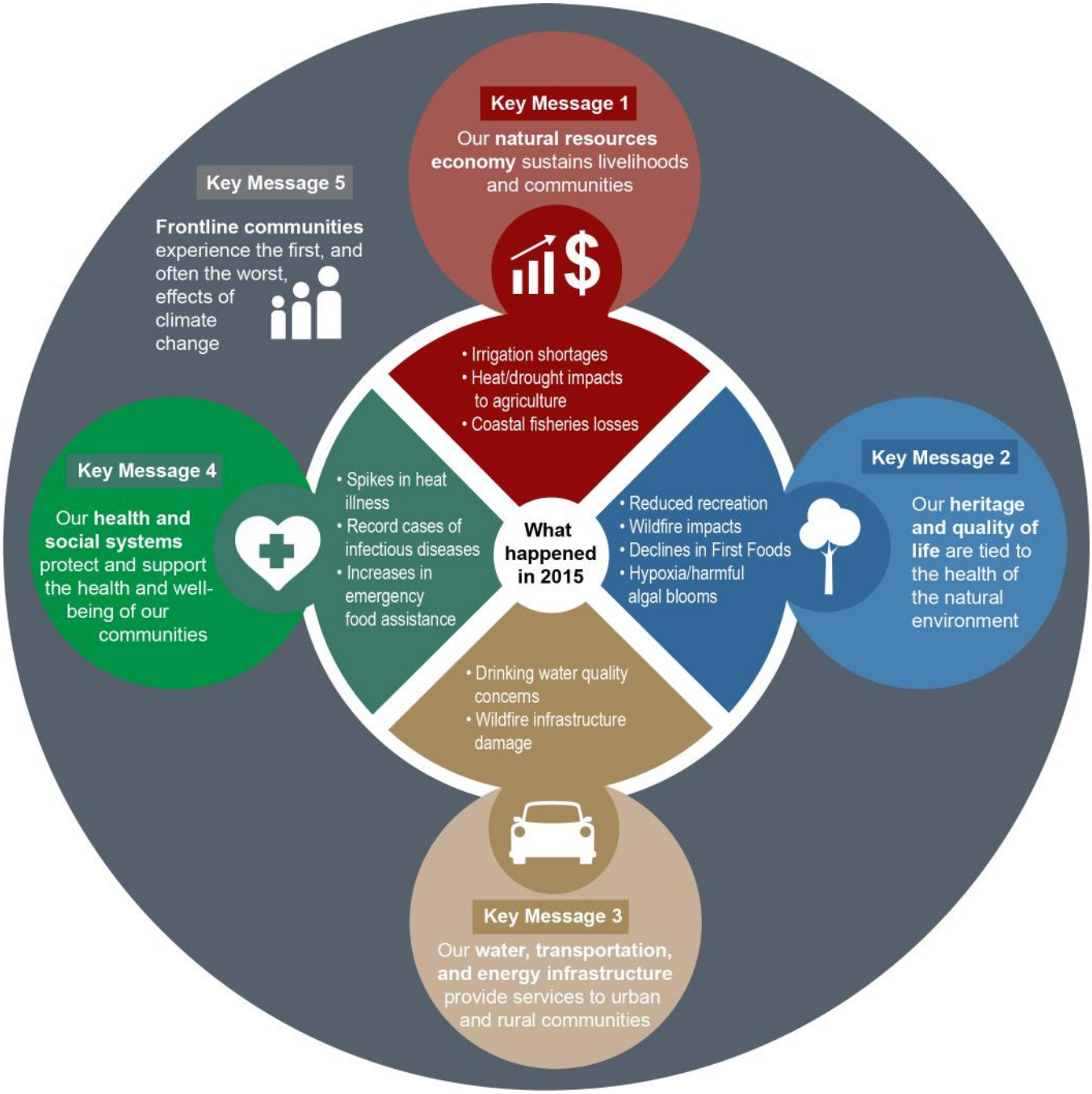


Figure 24.2: The climate-related events of 2015 provide a glimpse into the Northwest's future, because the kinds of extreme events that affected the Northwest in 2015 are projected to become more common. The climate impacts that occurred during this record-breaking warm and dry year highlight the close interrelationships between the climate, the natural and built environment, and the health and well-being of the Northwest's residents. Source: USGCRP.

Average winter precipitation is expected to increase over the long term, but year-to-year variability in precipitation is also projected to increase.[11] Years of abnormally low precipitation and extended drought conditions are expected to occur throughout the century,[11] and extreme events, like heavy rainfall associated with atmospheric rivers, are also anticipated to occur more often.[14] Along the coast, severe winter storms are also projected to occur more often, such as occurred in 2015 during one of the strongest El Niño events on

record.[15] El Niño winter storms contributed to storm surge, large waves, coastal erosion, and flooding in low-lying coastal areas (Ch. 8: Coastal, KM 1).[16] Changes in the ocean environment, such as warmer waters, altered chemistry, sea level rise, and shifts in the marine ecosystems are also expected (Ch. 9: Oceans). These projected changes affect the Northwest's natural resource economy, cultural heritage, built infrastructure, recreation, and the health and welfare of Northwest residents.

Key Message 1

Natural Resource Economy

Climate change is already affecting the Northwest's diverse natural resources, which support sustainable livelihoods; provide a robust foundation for rural, tribal, and Indigenous communities; and strengthen local economies. Climate change is expected to continue affecting the natural resource sector, but the economic consequences will depend on future market dynamics, management actions, and adaptation efforts. Proactive management can increase the resilience of many natural resources and their associated economies.

Linkage Between Observed Climate and Regional Risks

The Northwest provides for a diverse natural resource economy, from coastal fisheries, to Douglas fir plantations, to vineyards, to semiarid rangelands, to dryland and irrigated farms. The region is the Nation's top producer of 28 agricultural products, one of the leading national producers of timber products, and is widely recognized for salmon and shellfish fisheries. The agriculture, forestry, and fisheries sectors accounted for over 700,000 jobs and more than $139 billion in sales in 2015 (in 2015 dollars; Figure 24.3).[17]

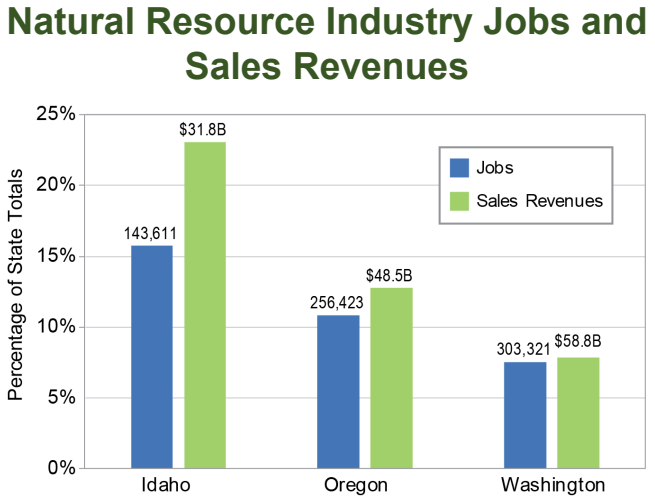


Figure 24.3: Natural resources are a key part of the Northwest economy. Climate change is putting natural resource sector jobs and sales revenues at risk. Jobs and sales figures include the agriculture, forestry, and fisheries sectors only, and are presented based on 2015 data for Idaho, Oregon, and Washington.[17] Source: U.S. Forest Service and Boise State University.

The outdoor recreation sector is another important contributor to local economies in the Northwest. The Outdoor Industry Association (2017)[18] estimates that the region's outdoor recreation economy generates $51 billion (based on 2017 data, dollar year not reported) in consumer spending each year and provides around 451,000 jobs. These economic benefits are particularly important in rural and tribal communities whose income base is largely dependent on natural resource economies and supporting industries (Ch. 10: Ag & Rural, KM 4; Ch. 15: Tribes). Outdoor activities, including skiing, boating, rafting, hunting, fishing, hiking, and backpacking, are impacted by climate variability, whether through less summer water, warmer streams, less snowfall, or loss of forests. Comparing high-snowfall to low-snowfall years in the Northwest between 1999 and 2009, each low-snowfall year resulted in more than 2,100 fewer employees and a $173 million reduction in ski resort revenues ($189 million in 2015 dollars) compared to the high-snowfall years.[19] Impacts on the skiing industry were especially prominent during

the warm 2015 winter, when snowpack was at record lows (see Box 24.7).

Both the natural resource commodity sector and the outdoor recreation industry are sensitive to short- and long-term climate variability. The record-setting 2015 drought and above-average temperatures were a challenge for agriculture. The reduced availability of water for irrigation coupled with heat stress impacted production and livestock health (see Box 24.7) (see also Ch. 10: Ag & Rural, KM 2 and 3; Ch. 3: Water, KM 3). In Northwest forests, tree mortality driven by wildfires, insects, and disease have been more prevalent over the last two decades due to drought conditions and increased temperatures (e.g., Hicke et al. 2013[13]), and timber managers are adjusting to increased risk of loss by shortening rotation rates, reducing investment in some areas, and changing planted species.[20,21]

Commercial fisheries are also sensitive to climate variability. River temperatures increase during warm and dry years, resulting in fish kills of migrating and spawning salmon; these fish kills have consequences several years in the future.[22,23,24] In 2015, July water temperatures in the lower Columbia River and its tributaries were higher than in any other year on record, leading to a high rate of mortality for endangered sockeye and threatened Chinook.[25,26] The record temperatures in 2015 were part of a long-term trend of declining low flows[27] and warming streams.[28,29] Increasing ocean temperatures and acidity also impact fish survival, species abundance, and predator–prey distribution and timing.[30] In 2015, the increased ocean temperatures were part of an ocean heat wave coined "the Blob," which fueled a coast-wide harmful algal bloom that affected commercial, recreation, and tribal subsistence fisheries (see Box 24.7) (see also Ch. 9: Oceans).[10]

Future Climate Change Relevant to Regional Risks

Shifts in timing of water supply, such as earlier snowmelt and declining summer flows, can adversely impact irrigated crop productivity, particularly where access to reservoir water storage and/or groundwater is limited (Ch. 10 Ag & Rural, KM 2).[31] Planning studies for Northwest reservoirs suggest a significant increased need for reservoir storage to meet future summer irrigation demands under climate change scenarios.[32,33] Irrigation demands among farmers in the Columbia River Basin are projected to increase 5% in response to climate change by the 2030s; however, actual water demands will vary depending on adaptive management decisions and crop requirements.[34] For dryland wheat production, shifting planting dates and rising temperatures coupled with increased atmospheric carbon dioxide (CO_2) and associated increases in plant water use efficiency are projected to lead to improved wheat yields under both lower and higher scenarios (RCP4.5 and RCP8.5) through the end of the century.[35,36]

Specialty crops, including apples and other tree fruits, are already experiencing changes. Higher spring temperatures have led to earlier flowering, which can lead to a mismatch with the availability of pollinators required for fruit setting (the process of flowers becoming fruit)[37] and can affect fruit quality as well as yield. Additionally, summer heat stress can lead to sunburn scald on apples and softer berry crops that can be damaged in transport and harvest,[37] which can decrease fruit quality and the farmers' selling price. Heat stress can also decrease livestock health and increase parasite abundance.[38] Projected warmer and drier summer seasons will likely reduce forage quality and quantity,[39] with varied impacts across forage and rangeland types.[40] Impacts to the quality and quantity of forage will also likely impact farmers' economic viability as they may need to buy additional feed or wait longer for their

livestock to put on weight, which affects the total price they receive per animal.

Forests in the interior Northwest are changing rapidly because of increasing wildfire[8] and insect and disease damage,[41,42] attributed largely to a changing climate (Ch. 5: Land Changes).[43] These changes are expected to increase as temperatures increase[44] and as summer droughts deepen.[45] For forests that grow in areas with snowpack, the declining snowpack is projected to worsen summer drought conditions, increasing vulnerability to drought caused by year-to-year precipitation variability.[46] Some forests in the region will increase in potential productivity (growth without consideration of increased disturbance) due to a combination of increased CO_2 and a longer growing season length, while others will decrease due to reduced availability of summer moisture (Ch. 6: Forests).[47] Timber supplies from the drier eastern Northwest forests are the most affected by climate-related disturbances,[48] resulting in intermittent and unpredictable timber supplies and depressed timber prices[49] in an already difficult global market. This could affect mill investments and the long-term viability of forestry as an economic activity, particularly in the more remote areas of the region where transportation costs to mills are high.

The negative impacts on Northwest fisheries associated with ocean warming, acidification, and harmful algal blooms are expected to increase (Ch. 9: Oceans).[50] This could lead to extensive fisheries closures across all of the region's coastal fisheries, with severe economic and cultural effects on commercial and subsistence shellfish industries. The warming ocean is projected to result in range shifts, with some Northwest species shifting as far north as the Bering Sea.[51] However, these range shifts may also open up new fishing opportunities in the Northwest,[51,52] depending on interstate and international coordination between management agencies. As the marine ecosystems respond to climate change, there will likely be consequences to existing place-based fisheries resources, as well as potential benefits and new resources. How the shifting resources will be managed and how existing fishing rights and allocations will change over time is currently not known (Ch. 9: Oceans, KM 2).

Projections for increased stream temperature indicate a 22% reduction in salmon habitat in Washington by late century under a high emissions future (the A1F1 scenario).[53] This habitat loss corresponds to more than $3 billion in economic losses due to reductions in salmon populations and decreases in cold-water angling opportunities ($3.3 billion in 2015 dollars, discounting method not specified).[53] Freshwater trout are sensitive to habitat connectivity and wildfire, so land management practices will affect how trout respond to climate change.[54] Overall, commercial fishing performance and abundance are expected to decline as the climate changes.[50,55,56,57]

Decreases in low- and mid-elevation snowpack and accompanying decreases in summer streamflow are projected to impact snow- and water-based recreation, such as downhill and cross-country skiing, snowmobiling, boating, rafting, and fishing. Climate change could decrease snow-based recreation revenue by more than 70% annually in the Northwest under a higher scenario (RCP8.5).[58] Impacts to snowpack and, consequently, winter recreation will likely occur later in the colder, higher-elevation mountains in southern Idaho.[59]

Challenges, Opportunities, and Success Stories for Reducing Risk

Climate change will likely have both positive and negative effects on the natural resource sector; however, cost-effective adaptation approaches that build agro-ecosystem

resilience are likely needed to maintain agricultural livelihoods (see Box 24.1). A shift in plant hardiness zones, or the ability of a given plant to thrive in a specific location, is expected, changing the suitability of growing certain crops in specific locations;[60,61] such shifts may change land uses entirely (Ch. 5: Land Changes, KM 2). For example, Northwest wine producers may see the potential for growing higher-quality and higher-value wine grape varietals,[62] but changing hydrologic regimes are projected to limit available water supplies for irrigation, requiring water storage or alternative water sources to maintain productivity. Over the longer term, changes to average growing season temperatures and the number of severe hot days are projected to reduce premium wine grape production in the Northwest, potentially shifting prime growing areas further north.[63] To take advantage of shifting opportunities, farmers would need to consider costly changes and investments in new farming practices and territories in advance of projected climate change.[37,64]

Livestock producers in the Northwest have an advantage over those in other U.S. regions where climate change impacts are likely to be more severe (Ch. 10: Ag & Rural, KM 3).[65] However, livestock production costs are still likely to increase in the Northwest due to supplemental feeding and watering requirements and the need for reducing livestock numbers in response to warmer and drier summers.[40]

The prevalence of wildfires, insect infestations, disease epidemics, and drought-induced dieback of Northwest forests have heightened forestry managers' awareness of potential climate change impacts. Over the long term, these sustained impacts are projected to fundamentally alter forest composition and land cover (Ch. 6: Forests, KM 1; Ch. 5: Land Changes). Forest management adaptation strategies are being developed,[21,66] including strategies

Supplemental Watering of Livestock During Drought

Figure 24.4: Supplemental watering of livestock in Eastern Oregon during the 2015 drought. Photo credit: Sonia A. Hall.

that address drought-related risks, improve the reliability of forest transportation infrastructure, and protect forest-related ecosystem services (Ch. 6: Forests, KM 3).[67] Vulnerability assessments and adaptation plans have been completed, or are in progress, for almost every National Forest and Park in the region.[68]

Marine and ocean environments of the Northwest are projected to continue to change gradually in response to climate change, but the full extent of the potential effects on fisheries is not well understood.[69] In the near term, the fisheries industry can use existing strategies that work within the limits of the natural environment to maintain species abundance, avoid extinction, or increase harvests, such as limited fishing seasons, developing quota systems, and expanding aquaculture (Ch. 9: Oceans, KM 2). In the longer term, particularly as large-scale range shifts occur,

species-dependent management changes and alternative management systems are likely to be needed to maintain fisheries and open up new fisheries opportunities.[70]

Despite the many strategies for reducing risks, adaptive capacity is not uniform across the natural resource sector. Given the heterogeneity across climatic and natural resource industries in the region, it is not likely that productivity gains and losses will be felt equally across the broad diversity in the region.[71,72]

Emerging Issues

Climate stressors such as increased temperatures, CO_2 fertilization, and precipitation changes are projected to impact pest, disease, and weed pressures (Ch. 10: Ag & Rural).[77,78] Improved modeling of climate stressors on yields and crop quality will likely enhance the understanding of climate change effects and inform adaptation options[36] and assist in addressing farmers' concerns about future pest and pathogen impacts in the region.[79,80] Water shortfalls are also likely to continue during drought periods despite adaptation efforts focused on water efficiency and reducing water usage (Ch. 3: Water, KM 1). Western water law assigns a priority date to each right based on seniority, so junior (or more recent) water rights are more likely to be adversely affected under shortage conditions than

Box 24.1: Adaptive Agricultural Approaches in Practice

Farmers and ranchers across the Northwest are creating resilient agro-ecosystems to reduce weather- and climate-related risks while meeting economic, conservation, and adaptation goals. Below are a few examples of these efforts from the region.

- A dryland farmer in Eastern Oregon is implementing flexible cropping methods, which allows the farmer to plant additional crops, instead of leaving the field uncultivated (fallow), when soil moisture conditions allow. By intensifying production and reducing fallow periods, profits have increased while also improving weed management, reducing erosion, and improving soil quality.[73]

- A vegetable, grain, and livestock farmer in Washington is caring for the soil by using conservation tillage, direct seeding, and double cropping to reduce soil erosion, improve soil health, and increase revenues.[74]

Figure 24.5: A farmer in Oregon surveys his no-till field, a practice used to build climate resilience. Photo credit: Sylvia Kantor, Washington State University Extension.

- A cattle ranching family in Washington is using holistic management, a comprehensive approach for ranch decision-making, to reduce environmental risks and improve pasture productivity and profitability.[75]

- Farmers in Oregon's Willamette Valley are using dry farming methods to reduce reliance on irrigation water. This Dry Farming Collaborative is developing and implementing approaches that reduce drought risks during dry summer growing seasons.[76]

those with senior water rights. More studies would enhance the understanding of which watersheds are at the greatest risk and what, if any, changes could address water limitations in the future. The development of more robust water markets may facilitate adaptation to climate change in the arid and semiarid Pacific Northwest; however, considerable institutional barriers currently prevent their full implementation.[81]

Although much is being researched with respect to the effects of climate change on forests and associated ecosystem services, far less has been explored with respect to timber markets. Even then, most of the focus has been on changes in forest productivity overall (e.g., Latta et al. 2010[47]) and less on the consequences of disturbance. Research is absent on the effects of potential increases in supply volatility and the consequences for investment and ultimately on harvest and milling jobs.

Ocean acidification poses a direct threat to shellfish and other calcifying species that are at the base of the food web (Ch. 9: Oceans, KM 1). The prominence of the impact on shellfish farms in the Northwest led to the installation of an ocean monitoring system to track ocean acidity. Although calcium carbonate can be used to increase seawater pH in a hatchery setting,[82] the same approach cannot be used in the open ocean to prevent shell dissolution.[83] The broader food web consequences of decline in calcifying species is an area of active research (Ch. 9: Oceans).

There is a great deal of uncertainty regarding impacts on the economic viability of primarily rural, natural-resource-based economies in the region, particularly the degree to which individual sectors are integrated into global commodity markets, which are likely to vary immensely and be difficult to predict (Ch. 10: Ag & Rural; Ch. 16: International, KM 4).[50]

Key Message 2

Natural World and Cultural Heritage

Climate change and extreme events are already endangering the well-being of a wide range of wildlife, fish, and plants, which are intimately tied to tribal subsistence culture and popular outdoor recreation activities. Climate change is projected to continue to have adverse impacts on the regional environment, with implications for the values, identity, heritage, cultures, and quality of life of the region's diverse population. Adaptation and informed management, especially culturally appropriate strategies, will likely increase the resilience of the region's natural capital.

Linkage Between Observed Climate and Regional Risks

The intangible values and aspects of the Northwest's natural environment that support a high quality of life for its residents—wildlife, habitat, and outdoor recreation—are at risk in a changing climate. Tribes and Indigenous communities that rely heavily on the natural environment for their culture and heritage are also at risk.

The Northwest's native wildlife is impacted by climate variability and change *directly* through temperature shifts, water availability, and extreme events, and *indirectly* through loss or fragmentation of habitat.[84] Changes in climate can alter the balance among competing species or predator–prey relationships (e.g., Wenger et al. 2011[52]). Three wildlife categories are of principal concern: already sensitive or endangered species, snow-dependent species, and game species. While the first two groups of animals are generally negatively impacted by changes in climate, some game species, such as deer and elk, may thrive. Game species are

First Salmon Ceremony of the Lummi Tribe, Washington

Figure 24.6: Tribes in the Northwest typically honor the first salmon caught in the season through tribal ceremonies. Photo credit: Northwest Indian Fisheries Commission (CC BY 3.0).

of concern not because of their sensitivity to changes in climate and habitat but because of their notable value for recreational hunting and as key cultural resources for tribes. Climate change is also projected to impact First Foods, or foods that tribes have historically cultivated for subsistence, economic, and ceremonial purposes. First Foods vary among tribes but often include berries, roots, water, fish, and local wildlife.[85,86] Additionally, nearly half of all adults in the region participated in wildlife-related recreation in 2010.[87] As temperatures increase, the demand for warm-weather outdoor and water-based recreation increases, and visitation rates at local, state, and national parks increase.[88,89,90] However, boating and other water-based recreation opportunities are likely to decline in the future when summer streamflows and reservoir levels are low. Additionally, popular winter sports and snow-based recreational activities, such as downhill skiing, cross-country skiing, and snowmobiling, have been dramatically impacted by reduced snowfall (see Box 24.7). In low-snowfall years, Washington and Oregon show the highest percentage drop of skier visits, meaning that residents and visitors are losing desirable skiing opportunities.[91]

Future Climate Change Relevant to Regional Risks

Wildlife responses to a changing climate are varied and complex (Ch. 7: Ecosystems). Some species, such as cavity nesting birds, will very likely benefit from greater disturbance.[92,93] Others, particularly snow-dependent species, will likely be unable to persist under climate change.[94]

Game species are expected to have diverse responses to climate change. Longer dry seasons and more pronounced droughts are projected to reduce wetland habitat extent and duration, causing changes in waterfowl movement. Increased fire disturbance, on the other hand, will likely increase shrub cover, a preferred food for deer and elk;[95] reduced winter snowpack may increase food availability in winter; and warmer temperatures reduce winter stress, all of which would support higher deer and elk populations. The primary climate-related impact on game species will likely come from increases in disease and disease-carrying insects and pests.[96]

Temperature-sensitive bull trout, salmon, and other water-dependent species, such as amphibians, are most vulnerable to increased habitat fragmentation.[97,98,99] Increased frequency of extreme events such as flooding, debris flows, and landslides are projected to alter habitats and likely cause local extinctions of aquatic species.

Increased winter streamflow and decreased summer flow are projected to threaten salmon spawning,[100] compromising salmon hatchery and reintroduction efforts.[101] Projected increases in winter storm intensity will likely lead to higher river flows and increased sediment loading that can bury salmon eggs and reduce salmon survival.[101] Rising stream temperatures, ocean acidification, and loss of nearshore and estuarine habitat also increase salmon mortality across all phases of the salmon life cycle.[102]

Shellfish beds are threatened by sea level rise, storm surge, and ocean acidification.[85,103] Species moving out of traditional hunting, gathering, and fishing areas are projected to impact resource access for many tribes.[101,104] Increasing wildfire frequency and intensity are changing foraging patterns for elk and deer, and increased prevalence of invasive species and disease will likely diminish both wildlife and foraging for traditional plants, berries, roots, and seeds.[105]

In winter, continued decreases in lower-elevation snowpack are projected to impact snow-based recreation.[19] Less snowpack and earlier melting of snowpack will likely result in decreased water availability, reducing the quality, quantity, and availability of water-based recreational opportunities, such as boating, rafting, and fishing.[18]

Increased wildfire occurrence is projected to degrade air quality and reduce the opportunity for and enjoyment of all outdoor recreation activities, such as camping, biking, hiking, youth sports, and hunting. Degraded air quality also directly impacts human health and quality of life (see Key Message 4).

Razor Clamming in Washington State

Figure 24.7: Razor clamming draws crowds on the coast of Washington State. This popular recreation activity is expected to decline due to ocean acidification, harmful algal blooms, warmer temperatures, and habitat degradation. Photo courtesy of Vera Trainer, NOAA.

Wildfires Affect Outdoor Recreation

Figure 24.8: Wildfires impact outdoor wilderness activities and recreation. Reduced air quality and closed trails and camping grounds are projected to increase as wildfire occurrences increase. Photo credit: Charles Luce.

Recreational ocean fishing opportunities are expected to decline under future climate change scenarios,[55,56,57] and it is likely that fishery ranges will change.[51] Recreational razor clamming on the coast is also expected to decline due to cumulative effects of ocean acidification, harmful algal blooms, higher temperatures, and habitat degradation (see Figure 24.7 and Key Message 1).

Challenges, Opportunities, and Success Stories for Reducing Risk

Historical and projected changes in amenities affecting the quality of life in the Northwest, such as wildlife, recreation opportunities, and edible plants, form a key challenge for managers of these resources. Informed management, however, can reduce the consequences to those who enjoy and value these resources. Sensitive and endangered plant and animal species currently require special management considerations due to historical habitat changes and past species declines. Management of these species can substantially constrain land and water management options, and the protection of these species will likely become more difficult as suitable habitat is lost.

Game species are already managed. Further management of waterfowl habitat is projected to be important to maintain past hunting levels. If deer and elk populations increase, the pressures they place on plant ecosystems (including riparian systems) may benefit from management beyond traditional harvest levels.

The cultural practice of harvesting and consuming First Foods is integral to tribes and Indigenous health (Ch. 15: Tribes).[106] Many tribes, such as the Confederated Tribes of the Umatilla Indian Reservation are using climate change vulnerability assessments and climate change adaptation plans to alter how First Foods are managed.[107] Tribes can exercise their sovereign rights to manage their resources in a self-determined and culturally appropriate manner, thereby increasing each tribe's adaptive capacity to respond to climate change impacts on tribal lands, foods, health, and cultures (see Box 24.2).[85,108,109] Tribes can also increase their adaptive capacity through regional networks, such as the Columbia River Inter-Tribal Fish Commission, that support tribal and Indigenous planning and management (see Key Message 5).

As fisheries become stressed due to climate change, additional management strategies are likely to be needed to maintain fish populations. Strategies that focus on habitat quality and quantity are likely to be the most successful.[110]

Box 24.2: Pacific Salmon and the Identity and Culture of Northwest Tribes

For most Northwest tribes and Indigenous peoples, salmon fishing is more than a cultural, subsistence, and economic act. The tribes view salmon as an extension of life and an indicator of environmental health, and loss of salmon is equated with the loss of tribal identity and culture. As a testament of the importance of salmon, Julia Davis-Wheeler, a Nez Perce elder, stated: "We need the salmon because it is part of our lives and part of our history. The salmon is a part of us, and we are a part of it. Our children need to be able to feel what it is like to catch and eat salmon. They need to be able to experience that sense of respect that many of us have felt in past years."[111]

Figure 24.9: Pacific salmon are essential to most Northwest Tribes' identity and culture. Typically, the first salmon caught is displayed, cleaned, and cooked for the community to share. The skeleton is returned to the water to show respect to the salmon. This photo shows the First Salmon ceremony of the Puyallup Tribe. Pacific salmon—a keystone species in the Northwest—are at risk because of climate change. Economic, social, and cultural values are also at risk if salmon populations continue to decline. Recreational salmon fishing contributes to the quality of life and well-being for many Northwest residents. Photo credit: Matt Nagle, Puyallup Tribal News.

Adaptation strategies aimed at restoring and enhancing salmon fisheries can be more successful when traditional knowledge is coupled with modern science.[112,113] For example, the Nez Perce Tribe used local tribal knowledge to construct "natural" rearing ponds in the Columbia River coupled with introducing wild salmon as broodstock to enhance and restore a culturally significant salmon population.[109] Adaptation and informed management can reduce the consequences to those who enjoy and value these resources.

Emerging Issues

Some of the species likely to be affected by climate change are already imperiled by population declines, extirpations, or even extinction as a result of historical changes in habitat and other factors. Climate change adds urgency to addressing existing and emergent challenges. Research is already active in identifying resilient habitats (e.g., Morelli et al. 2016, Luce et al. 2014, Isaak et al. 2016[114,115,116]) and the means for maintaining and improving habitat resilience in the face of increasing climate and disturbance pressure.[117] Habitat modeling that includes projections of natural resource shifts, fragmentation, and identification of new wildlife corridors are projected to be beneficial in supporting land and water management decisions that benefit people, recreation, and the Northwest's varied wildlife.

An institutional network of land, wildlife, and fishery management agencies, tribes, and non-governmental conservation organizations has already successfully reversed negative trends in many fish and wildlife populations caused by other human activities.[118] These same groups are exploring methods to improve fish and wildlife resilience in a changing climate. Many habitat improvement activities, a cornerstone of conservation biology, also provide flood mitigation, climate mitigation, adaptation, and ecosystem service co-benefits (Ch. 6: Forests).[119,120] Despite proactive management and adaptation, it is likely that species not currently listed as endangered could become endangered over the next century, and eventual extinctions are likely, yet challenging to predict.[121]

First Foods are an important aspect of tribal and Indigenous health and well-being,[122] and they can be used as indicators in tribal health assessments and climate adaptation plans.[112,123] The loss or decline of First Foods is projected to have cascading physical and mental health impacts for tribes and Indigenous peoples (see Key Message 5) (see also Ch. 15: Tribes, KM 2).[124,125] However, more research to refine these indicators would better support decision-making (see Box 24.2).[123,126]

Social indicators link a decline in quality of life in the Northwest to loss of recreational opportunities due to climate change impacts,[127] but the causal links are not well understood. Additionally, future human migration and population increases may alter the relationship and nature of recreation in the Northwest.[128] As the population increases, the demand for snow-based recreation is likely to also increase. However, it is not clear how the limited availability of snow-based recreation (for example, a shorter ski season) in the Northwest over the long term can influence interest in snow sports in contrast to alternatives.

Key Message 3

Infrastructure

Existing water, transportation, and energy infrastructure already face challenges from flooding, landslides, drought, wildfire, and heat waves. Climate change is projected to increase the risks from many of these extreme events, potentially compromising the reliability of water supplies, hydropower, and transportation across the region. Isolated communities and those with systems that lack redundancy are the most vulnerable. Adaptation strategies that address more than one sector, or are coupled with social and environmental co-benefits, can increase resilience.

Linkage Between Observed Climate and Regional Risks

Infrastructure plays a critical role in keeping the Northwest's economy running smoothly. Roads, highways, railways, and ports facilitate the movement of people and goods within the region and support valuable import and export markets. Powerlines and substations maintain the reliable supply of electricity to homes, businesses, schools, and hospitals. Dams and reservoirs manage streamflow to minimize flood risks, generate electricity, and provide water supply for irrigation and human consumption. Groundwater wells act as an important water source for agriculture and drinking supplies across much of the region. Levees and seawalls prevent damage to homes and property along rivers and the coast. Culverts manage water flows to protect roadways from flooding and assist with fish passage, including for migrating salmon. Storm water and wastewater systems help minimize flooding, especially in urban areas, and are critical for maintaining water quality. However, most infrastructure is designed for a historical climate, and damage and disruptions caused by extreme events demonstrate existing infrastructure vulnerabilities that are likely to increase in a changing climate (Ch. 3: Water, KM 2; Ch. 4: Energy, KM 1; Ch. 11: Urban, KM 2; Ch. 12: Transportation, KM 1; Ch. 28: Adaptation, KM 2).

Services provided by infrastructure can be disrupted during extreme weather and climate events, illustrating the sensitivity of these systems to climate variability and change (see Box 24.3). During the 2015–2016 extreme El Niño winter, wave energy along the West Coast was about 50% above normal.[16] Several major storms hit northwestern Oregon, bringing record-breaking rainfall, high winds, and high tides. Tillamook County in Oregon experienced a state of emergency that included major highway and road closures due to flooding, failed culverts, landslides, and sinkholes. Disruptions in transportation networks affected access to food, healthcare, and social services (see Key Message 2) (see also Ch. 12: Transportation, KM 2).[130] The event highlighted the need to maintain detour routes that were valuable in reaching communities that could become isolated. Wave and storm surge energy

Box 24.3: Tribal Relocation as a Last Resort

The Quinault Indian Nation (QIN), located on the southern coast of Washington's Olympic Peninsula, has experienced repeated flood disasters, as described in the U.S. Climate Resilience Toolkit.[129] In March 2014, coastal storm surge breached the seawall protecting the town of Taholah, flooding the lower village. In January 2015, heavy rainfall washed out roads, including the Highway 109 bridge, a main access road to and from QIN, and threatened wastewater treatment facilities. With more severe impacts anticipated with climate change, combined with risks from tsunamis, QIN's leadership developed a master plan to relocate the lower village to higher ground. The master plan is considered the first step toward realizing QIN's vision for relocation based on sustainable practices and cultural values. Other Washington tribes have also relocated or begun relocation efforts, including the Hoh Tribe, Quileute Tribe, Makah Tribe, and Shoalwater Bay Tribe. Relocation of a tribe is considered a last resort.

Figure 24.10: Coastal floodwaters inundated the Quinault Indian Nation's lower village of Taholah in March 2014. This event, and continuing concerns about future climate change, prompted the village to begin relocation to higher ground. Photo credit: Michael Cardwell.

along the Pacific Northwest coast is expected to increase with climate change.[131] Continuing efforts to build resilience within the health and transportation sectors in response to flooding hazards will likely help the county weather future storms.[130]

Heavy rainfall can lead to slope instabilities and landslides, which can close roadways and railways. Along the Amtrak Cascades Corridor, more than 900 coastal bluff landslides have blocked the tracks and shut down rail service since 1914, with over 240 disruptions occurring between 2009 and 2013.[132] Each landslide results in a minimum 48-hour moratorium on commuter rail service. The Washington State Department of Transportation is implementing a Landslide Mitigation Action Plan to proactively address the climatic and other factors contributing to landslide-based rail closures.[132]

Landslides during winter storms have also closed major Interstates, such as the December 2015 closure of eastbound Interstate 90 near Snoqualmie Pass and the February 2017 closure of westbound Interstate 90 near Issaquah.

Wildfires can result in road and railway closures, reduced water quality in reservoirs, and impacts on the energy sector. The Goodell wildfire in August 2015 forced Seattle City Light to de-energize transmission lines around its Skagit River Hydroelectric Project for several days.[133] The combined impact of damages and lost power production totaled nearly $3 million (in 2015 dollars).[134] The Eagle Creek fire along the Washington–Oregon border in 2017 led to the closure of Interstate Highway 84 and an adjacent railway, likely increasing shipping costs and creating negative economic impacts on tourism and regional small businesses.[135]

Drought conditions also present challenges for infrastructure, especially water supplies. In Washington, the Department of Ecology allocated almost $7 million in drought relief funds in 2015 (in 2015 dollars). Relief grants were used to provide backup or emergency water supplies for irrigation or human consumption where wells were failing or pumping capacity was inadequate.[136] These small and typically rural systems are relatively more vulnerable to drought impacts when compared to larger urban systems (Ch. 10: Ag & Rural, KM 4).

Future Climate Change Relevant to Regional Risks

Climate change is expected to increase the frequency and/or intensity of many extreme events that affect infrastructure in the Northwest. Available vulnerability assessments for infrastructure show the prominent role that future extremes play. Since much of the existing infrastructure was designed and is managed for an unchanging climate, changes in the frequency and intensity of flooding, drought, wildfire, and heat waves affect the reliability of water, transportation, and energy services.

Hydrologic change will likely be an important driver of future climate stress on infrastructure. As higher temperatures increase the proportion of cold season precipitation falling as rain rather than snow, higher streamflow is projected to occur in many basins, raising flood risks.[137,138,139,140] An increased risk of landslides is also expected, as more mixed rain and melting snow events occur in low- to mid-elevation mountains.[141] Increases in the amount of precipitation falling in heavy rainfall events (including atmospheric rivers)[142] are anticipated to magnify these risks. Along the coast, sea level rise is projected to increase flood risks in low-lying areas and will likely magnify the potential for coastal erosion (Ch. 5: Land Changes) and infrastructure damage during extreme events with high storm surge and wave hazards. By the end of the century, the upper sea level rise projection of 4.3 feet[143] would impact significant infrastructure investments throughout the Northwest, particularly in the low-lying urban areas of the Puget Sound and Portland (Ch. 8: Coastal).

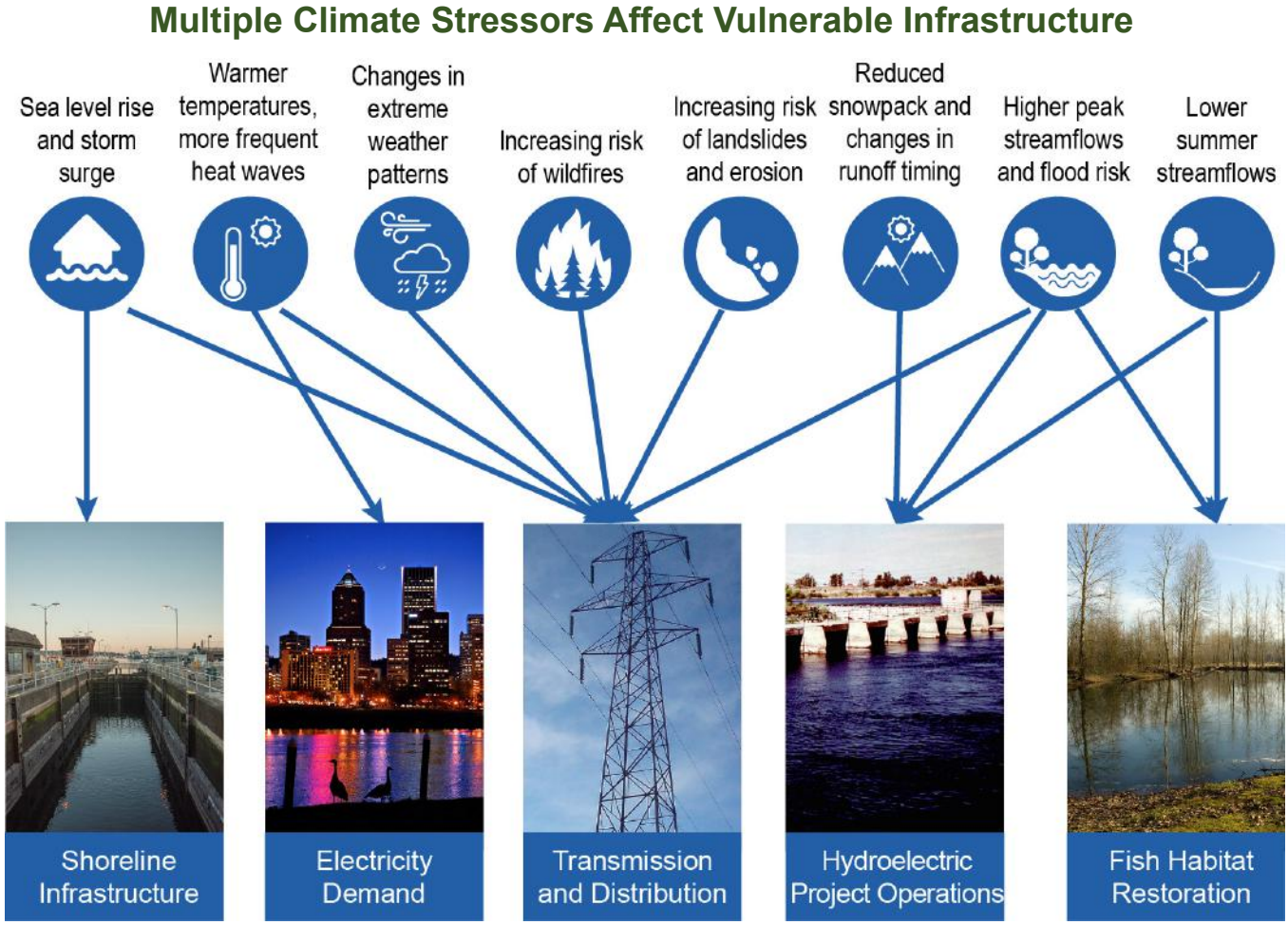


Figure 24.11: Extreme events such as floods, heat waves, wildfires, landslides, and drought play an important role in the vulnerability of infrastructure. The figure, from Seattle City Light's Vulnerability Plan,[133] illustrates how the utility's assets, operations, and management goals are affected by a broad range of climate impacts and extreme events. Adaptation strategies to increase the resilience of the energy system must focus on multiple potential risks as well as environmental considerations. Source: adapted from Raymond 2015.[133] Photo credits (from left to right): Emmet Anderson (Flickr, CC BY-NC 2.0), Justin Miller (Flickr, CC BY-NC 2.0), photojojo3 (Flickr, CC BY 2.0), U.S. Department of Energy, Rick Swart, Oregon Department of Fish & Wildlife.

Spring and summer streamflows are anticipated to decline in basins that have historically relied on snowmelt, and low flow periods are projected to be more prolonged and more severe. If observed declines in higher elevation precipitation continue,[144] this would exacerbate low streamflow conditions,[27] resulting in decreased water supply and reservoir storage. Climate change can affect water quality as well (Ch. 3: Water, KM 1). Higher air temperatures, lower streamflow, and decreases in rainfall are expected to raise summer stream temperatures, making it more difficult to meet water quality standards. In coastal areas, sea level rise will likely lead to saltwater intrusion into groundwater supplies.

Challenges, Opportunities, and Success Stories for Reducing Risk

Anticipated future impacts on infrastructure create opportunities for addressing existing environmental and social goals. For example, actions by the city of Boise, Idaho, to improve water quality are likely to minimize some of the impacts associated with a warmer climate. In Boise, a phosphorous removal facility reduces the amount of phosphorous entering rivers, thereby reducing the need for water treatment facility upgrades[145] and perhaps also preventing downstream algal blooms, which are anticipated to become more common in a warmer climate.

The Northwest has several examples of successful cross-sector collaboration between resource managers and scientists to plan and prepare for climate impacts across multiple sectors (Ch. 17: Complex Systems, KM 3). In Portland and Multnomah County, Oregon, the 2030 Climate Change Preparation Strategy and 2050 Climate Action Plan have incorporated strategies across multiple sectors including water systems, natural and built infrastructure, and human health, with specific social equity considerations woven throughout.[146,147] For many socially vulnerable populations, limited access to transportation, businesses, and other community resources can inhibit their ability to cope with climate impacts. Addressing these disparities can have the added benefit of bolstering resilience (see Key Message 5). Building and strengthening partnerships across sectors will continue to be important in addressing these complex challenges.

Infrastructure managers in larger urban areas like Seattle and Portland have invested in building climate resilience for their systems (e.g., Vogel et al. 2015, Mauger et al. 2015[139,148]) (see also Ch. 11: Urban, KM 4), often partnering with researchers to develop tailored climate risk information and adaptation strategies. However, in many parts of the Northwest, especially areas outside urban centers, the lack of redundancy within infrastructure systems will likely be an important factor in limiting adaptive capacity (Ch. 12: Transportation, KM 2; Ch. 10: Ag & Rural, KM 4). Understanding the risks associated with these systems remains a challenge, as impacts could emerge directly from climate events or from the interaction of non-climate and climate stressors (such as equipment failure making a water system more susceptible to subsequent drought). For example, in the Washington Department of Transportation's vulnerability assessment, lifeline roadways that serve as the only means to access communities often emerged as highly vulnerable.[149] Disruptions to these roadways could cut off communities, preventing supplies or first responders from arriving. The lack of redundancy in transportation networks has also been noted for several of the region's National Parks, contributing to their vulnerability.[141] In a similar vein, the Washington Department of Health is examining aspects of groundwater systems that contribute to climate vulnerability. They have found that many groundwater systems are single source and lack any back-up supplies (see Figure 24.12). If supplies are disrupted, either by climate or non-climate stressors, surrounding communities may be forced to transport water to their area or relocate to a place with a more reliable supply (Ch. 3: Water, KM 2).

An additional challenge in addressing future impacts to infrastructure is cost. Projects for replacing, retrofitting, or improving dams, reservoirs, pipelines, culverts, roadways, electrical transmission and distribution systems, and shoreline protection can have costs in the billions (e.g., Wilhere et al. 2017[150]).

Managing water in the face of a changing climate also presents an opportunity for transboundary collaboration and coordination. For the Columbia River, projections of future streamflow have been generated for use by U.S. federal agencies, in partnership with Canadian agencies.[151] The information about future hydrology can support infrastructure decisions about water supply management, flood risk management, and hydropower production (Ch. 3: Water, KM 3; Ch. 16: International, KM 4).

Emerging Issues

Infrastructure managers are beginning to consolidate planning for the combined risks of sea level rise, flooding, and seismic hazards, as well as tsunami risks that can also arise from a major earthquake event. Going forward, it could be useful to identify strategies that enhance community resilience and emergency

Single-Source Water Systems in Washington

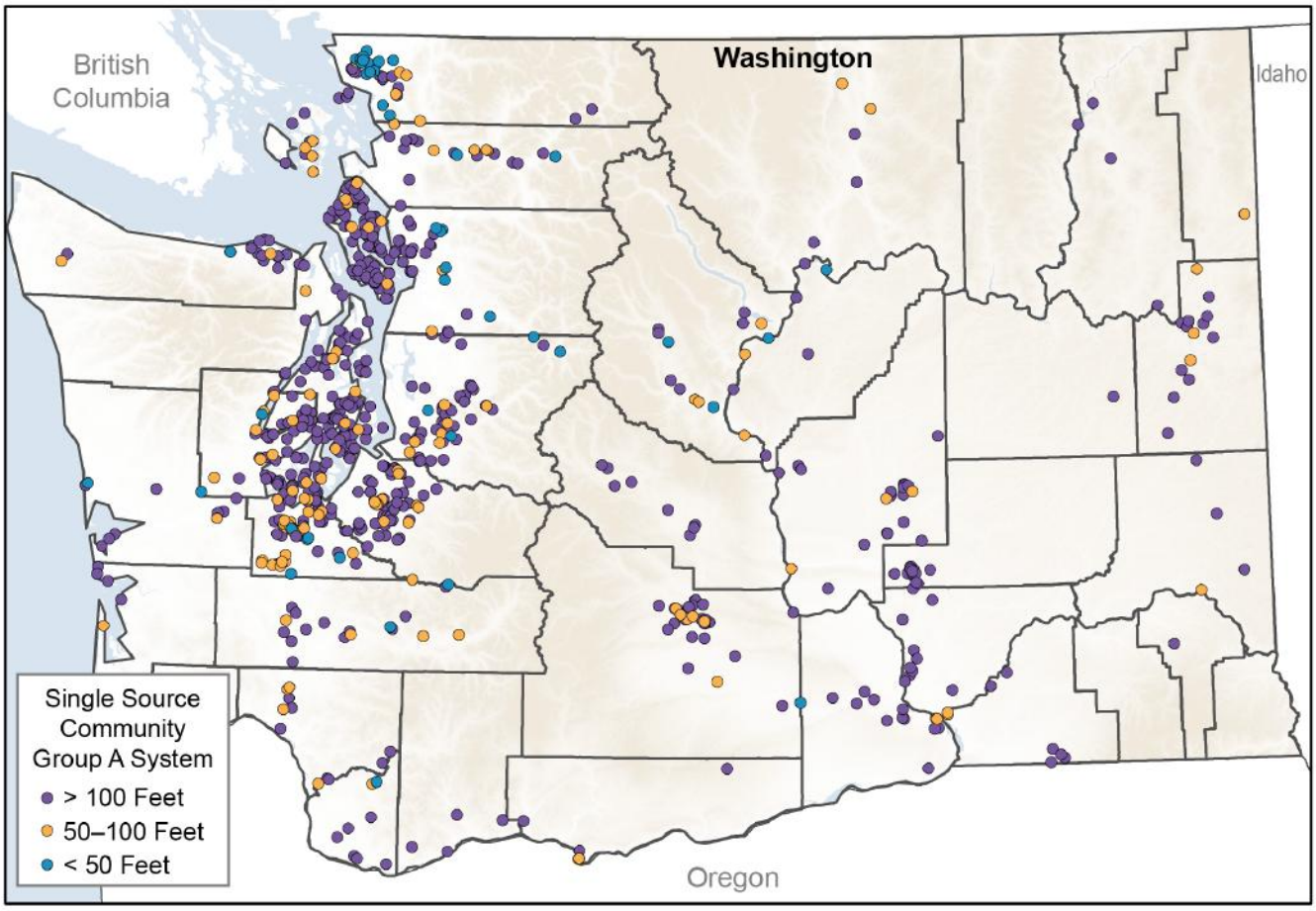


Figure 24.12: The map shows public water systems in Washington that are single source, meaning they lack a backup supply, and service at least 25 people per day or have 15 or more connections. Smaller public water systems exist but are not shown. For operators of single source systems, it will likely be particularly difficult to deal with climate-related disruptions such as flooding, drought, and saltwater intrusion. Approximate well depth is indicated by color; shallower wells (less than 100 feet in blue and orange) are projected to be more vulnerable to impacts, although aquifer type also influences vulnerability. Although similar impacts will likely occur in Oregon and Idaho, the data are not readily available to assess at a statewide level. Source: Washington Department of Health.

response capacity to many types of hazards and potential disruptions.

Infrastructure management is traditionally oriented to protecting assets and services in place. The use of "green" or hybrid "green and gray" infrastructure (e.g., Kittitas County Flood Control Zone District 2015, City of Portland 2010[152,153]) that utilizes nature-based solutions is emerging as a potential adaptation option. However, in some locations and for some impacts, it may be more efficient to remove or abandon infrastructure and find alternatives (for example, relocating communities and distributing water or energy systems). The knowledge and experience are just emerging to identify thresholds when such transformative decisions might be appropriate (Ch. 11: Urban, KM 3; Ch. 17: Complex Systems, KM 4).

Key Message 4

Health

Organizations and volunteers that make up the Northwest's social safety net are already stretched thin with current demands. Healthcare and social systems will likely be further challenged with the increasing frequency of acute events, or when cascading events occur. In addition to an increased likelihood of hazards and epidemics, disruptions in local economies and food systems are projected to result in more chronic health risks. The potential health co-benefits of future climate mitigation investments could help to counterbalance these risks.

Linkage Between Climate Change and Regional Risks

Over the last few decades, an increase in climate-related extreme events has led to an increase in the number of emergency room visits and hospital admissions. Warmer and drier conditions during summer have contributed to longer fire seasons.[140] Wildfire smoke can be severe, particularly in communities in the eastern Northwest.[154] Smoke events during 2004–2009 were associated with a 7.2% increase in respiratory hospital admissions among adults over 65 in the western United States.[155] In Boise, Idaho, 7 of the last 10 years have included smoke levels considered "unhealthy for sensitive groups" (including children) for at least a week during the fire season,[154] causing some cancellation of school-related sports activities (Ch. 13: Air Quality, KM 2).

During extreme heat events in King County, Washington, from 1990 to 2010, heat-related hospital admissions were 2% higher and deaths 10% higher than the average for that period,[156,157] with an increased demand for emergency medical services for children, outdoor laborers, and the elderly.[158] The state of Oregon has also recorded spikes in heat-related emergency room visits.[159] In particular, agricultural workers are at increased risks for heat-related injuries because they work outside during the summer harvest season.[160]

In the last several years, the region has seen an increase in some infectious diseases. An increase in Lyme disease cases is associated with rising temperatures and changing tick habitat.[161] The Washington Department of Health's vector surveillance program has observed an earlier onset of West Nile virus-carrying mosquitoes, likely associated with higher temperatures, and an increasing number of human infections, with some resulting in fatalities.[162] Before 1999, cryptococcal infections were limited to the tropics, but *Cryptococcus gatti*, the species that causes these infections, is now established in Northwest soil, with 76 cases occurring in Oregon in 2015.[163] The Oregon Health Authority recorded spikes in cases of Salmonella and *E. coli* during months with extreme heat in 2015.[163] A large outbreak of Shigellosis (a bacterial diarrheal disease) occurred in late 2015, affecting a large number of homeless people in the Portland Metro region; this outbreak was associated with unusually extreme precipitation.[164]

Changes in drought conditions and increased water temperatures have increased the potential for freshwater harmful algal blooms in recreational waters,[165] although there is little capacity among state health departments to monitor and track harmful algal blooms. Toxins from marine harmful algal blooms can accumulate in shellfish, leading to illnesses for those who eat them.[166] In 2015, during the largest harmful algal bloom ever observed off the West Coast from California to Alaska, high levels of domoic acid led to the closure of shellfish harvesting in much of the Northwest (Box 24.7).[167]

Children and youth, in general, will likely experience cumulative physical and mental health effects of climate change over their lifetimes[168] due to increased exposure to extreme weather events (such as heat stress, trauma from injury, or displacement) and increased toxic exposures (such as increased ground-level ozone pollution in urban areas or increased risk of drinking water contamination in rural areas). Beginning at the fetal development stage, environmental exposures to air or water pollution can increase the risk of impaired brain development,[169] stillbirth,[170] and preterm births.[171,172] Infants and children can be disproportionately affected by toxic exposures because they eat, drink, and breathe more in proportion to their body size.[173] Natural disasters, as well as gradual changes (like changing landscapes and livelihoods) caused by climate stressors, increase the risk of anxiety, depression, and post-traumatic stress disorder (PTSD).[174] Evidence shows that exposure to both pollution and trauma early in life is detrimental to near-term health, and an increasing body of evidence suggests that early-childhood health status influences health and socioeconomic status later in life.[175,176]

Future Climate Change Relevant to Regional Risks

More frequent wildfires and poor air quality are expected to increase respiratory illnesses in the decades to come (Ch. 13: Air Quality, KM 2). Airborne particulate levels from wildfires are projected to increase 160% by mid-century under a lower scenario (RCP4.5),[177] creating a greater risk of smoke exposure through increasing frequency, length, and intensity of smoke events.[177]

Projected increases in ground-level ozone (smog), small particulate matter ($PM_{2.5}$), and airborne allergens[178] can further complicate respiratory conditions (Ch. 13: Air Quality, KM 1). There is a well-documented link between exposure to air pollution and risk of heart attack, stroke, some types of cancer, and respiratory diseases,[179] all of which are leading causes of death in the Northwest.[180] The portion of each health condition attributed to air pollution is unknown, but the social and economic costs of these diseases are large. In Oregon, the medical costs associated with heart attacks in 2011 alone were over $1.1 billion, and those associated with stroke were $254 million ($1.2 billion and $269 million, respectively, in 2015 dollars).[181]

Increases in average and extreme temperatures are projected to increase the number of heat-related deaths.[182,183] Mid-century climate in Portland, Oregon, under a mid-high scenario (RCP6.0) may result in more than 80 additional heat-related deaths per year, although this figure does not account for future population growth or possible adaptations.[184]

Future extreme precipitation events could increase the risk of exposure to water-related illnesses as the runoff introduces contaminants and pathogens (such as *Cryptosporidium*, *Giardia*, and viruses) into drinking water.[185] In the Puget Sound, under a mid-high emissions scenario (SRES A1B), local atmospheric heating of surface waters is projected to result in 30 more days per year that are favorable to algal blooms and an increased rate of bloom growth.[186]

Income loss associated with climate impacts will likely increase the risk of people experiencing food insecurity (see Key Message 1).[187] As an example, in early 2016 a harmful algal bloom impacted the local economy in Long Beach, Washington, which is largely dependent on shellfish, tourism, and service industries. The local Food Bank recorded an almost 25% increase in the number of families requesting assistance in the six months that followed.[188] Climate-driven hardships can also affect mental health, resulting in outcomes ranging from

stress to suicide.[189] Oregon, Washington, and Idaho all rank among the top 10 states in terms of prevalence of mental illness and lowest access to mental health care.[190] Serious mental illness costs the U.S. economy more than $193 billion in lost earnings each year ($224 billion in 2015 dollars).[191] Tribes and Indigenous peoples face multiple physical and mental health challenges related to climate change, with impacts to subsistence and cultural resources (see Key Messages 2 and 5) (see also Ch. 15: Tribes, KM 2). Some of these health concerns are described in a recent project created by members of the Confederated Tribes of Warm Springs.[192] Tracking climate stressors and training related to climate anxiety and post-disaster trauma is not widespread among the region's health workforce.[193]

Challenges, Opportunities, and Success Stories for Reducing Risk

Existing environmental health risks are expected to be exacerbated by future climate conditions,[187] yet over 95% of local health departments in Oregon reported having only partial-to-minimal ability to identify and address environmental health hazards.[194]

With funding from the Centers for Disease Control and Prevention, Oregon has been able to make some headway on assessing climate change vulnerabilities[195] and recently released a statewide climate and health resilience plan.[196] Five local health jurisdictions in Oregon are some of the first in the country to complete local climate and health adaptation plans. Interventions to address community-identified priorities range from providing water testing for domestic well users in drought-prone areas to quantifying the health co-benefits of proposed transportation investments. The Washington Department of Health has also added a climate program to begin integrating climate considerations into the state's public health system. In addition, the Drinking Water State Revolving Fund has made it possible for water system managers and utilities to apply for low interest loans that support resilience projects. Washington's Marine Biotoxin Program, also housed within the Department of Health, operates an early warning system in partnership with academics, organizations, and citizen scientists to increase the geographic breadth and frequency of sampling for harmful algal blooms that could compromise the safety of shellfish. Public health practitioners in southeastern Idaho have formed a new working group with tribes, universities, local jurisdictions, businesses, and nonprofits to develop strategies for mitigating health impacts of wildfire smoke and water insecurity.

Together, Northwest states have launched the Northwest Climate and Health Network for public health practitioners to share resources and best practices. Idaho, Oregon, and Washington all have syndromic surveillance systems that provide near-real-time data from emergency room visits. These health data have the potential to be layered with climate and environmental data (such as temperature and air quality data), but such analysis has not been carried out on a broad scale.

Incorporating more health and wellness considerations into climate decision-making can increase a community's overall resilience (Ch. 14: Human Health, KM 3). For example, preserving the ecological functions of an area can also promote tribal and Indigenous health, while investing in active transportation and green infrastructure can also improve air quality and increase physical activity.[197]

Box 24.4: Healthcare Partnerships That Increase Resilience

A new International Transformational Resilience Coalition (ITRC) has grown out of the Northwest and is engaging cross-sector partners in pilot projects to build psycho-social resilience in some communities. The initiative uses neuroscience and mindfulness to train leaders and organizations on how to cope with, and use, climate-related adversities to catalyze collective adaptation.[193] Composed of more than 250 mental health, trauma treatment, resilience, climate, and other professionals, the ITRC is working to enhance the ability of organizations and communities to heal, grow, and flourish during economic, social, and environmental stress and adversity.

Figure 24.13: Participants at the 2017 Northwest International Transformational Resilience Coalition Conference on Building Psycho-Social Resilience to Climate Change. Photo Credit: The Resource Innovation Group/International Transformational Resilience Coalition.

Emerging Issues

Communities with higher rates of illness and death often have less adaptive capacity and are more vulnerable to climate stressors.[198] Many people living in the Northwest already struggle to meet basic needs that could serve as protective factors—and these numbers could increase. For example, roughly 1 in 5 children in the region live in a food-insecure household[199,200,201] and are already at higher risk of poor health outcomes like asthma and diabetes.[202] Both the states of Washington and Idaho have had some of the largest increases in homeless populations in the United States, and in 2016, Oregon had the highest rate of unsheltered homeless families with children.[203] People lacking adequate shelter face increased climate risks (such as direct exposure to extreme heat or winter storms) while also having increased vulnerability (such as poorer health and less access to resources).

Displacement and increased migration to the Northwest could place increasing pressures on housing markets, infrastructure, and health and social service systems.[128] However, the role of climate as a driver for migration to the Northwest is speculative; current population forecasts do not yet account for climate factors.[204]

Public health leaders in the Northwest are working to modernize health systems to better respond to and prepare for complex and emerging health risks. Coordinated Care Organizations (CCOs) in Oregon, which serve as Medicaid insurance providers, are beginning to invest in certain climate protections for members. For example, some are covering the cost of air conditioning units for patients at risk of heat-related illnesses, ensuring patients can remain in their homes.[205] More studies would be needed to fully account for the cost savings associated with these kinds of health-related services.

Key Message 5

Frontline Communities

Communities on the front lines of climate change experience the first, and often the worst, effects. Frontline communities in the Northwest include tribes and Indigenous peoples, those most dependent on natural resources for their livelihoods, and the economically disadvantaged. These communities generally prioritize basic needs, such as shelter, food, and transportation; frequently lack economic and political capital; and have fewer resources to prepare for and cope with climate disruptions. The social and cultural cohesion inherent in many of these communities provides a foundation for building community capacity and increasing resilience.

Linkage Between Observed Climate and Regional Risks

Because people care about the place they live, a focus on places serves to highlight the local material and symbolic contexts in which people create their lives and through which those lives derive meaning.[206,207] This is true for communities across the Northwest whether or not they are on the frontline of dealing with climate change. While there are many types of frontline communities (those communities likely to experience climate impacts first and worst) in the region, this chapter highlights three sets of communities: tribes (Ch. 15: Tribes), farmworkers, and low-income populations in urban and rural (Ch. 10: Ag & Rural) environments.

The effects of climate variability and extreme events are not felt equally across communities in the Northwest. Frontline communities have higher exposures, are more sensitive, and are less able to adapt to climate change for a variety of reasons (Ch. 14: Human Health, KM 1),[187,208,209] including enhanced occupational exposure,[210] dependence on natural and cultural resources (Ch. 15: Tribes, KM 1),[124] fewer economic resources,[209] other demographic factors,[211,212] and gender.[213] In addition, frontline communities frequently must overcome cumulative exposures[125] and intergenerational and historical trauma.[125,214] It is the interconnected nature of legacy exposure, enhanced exposure, higher sensitivity, and less capability to adapt that intensifies a community's climate vulnerability.[187,215,216] Climate change can affect the health, well-being, and livelihoods of these communities directly by increasing the risk of acute health impacts, such as physical injury during severe weather,[189,209] and indirectly through chronic impacts, such as food insecurity or mental health conditions like PTSD (see Key Message 4) (see also Ch. 15: Tribes, KM 2; Ch. 14: Human Health, KM 1).

Future Climate Change Relevant to Regional Risks

Frontline communities generally prioritize meeting existing basic needs, such as shelter, food, and transportation. While climate-related risks vary from community to community, neighborhood to neighborhood, and even person to person, for frontline communities, climate variability, change, and extreme events can exacerbate existing risks, further limiting their ability to meet basic needs.[217]

Northwest tribes directly depend on natural resources, both on and off reservations, and are among the first to experience climate impacts. In the United States, the history of colonization, coupled with ongoing management barriers (such as land fragmentation and limited authority and control over natural resources), has led to many challenges for tribal and Indigenous climate adaptation (see Box 24.5) (see also Ch. 15: Tribes, KM 3).[124,218] The loss or reduced availability of First Foods (Key Message 2) can have broad physical, cultural,

and spiritual impacts, including diabetes, heart disease, mental health impacts, and loss of cultural identity.[125,209] This is likely to be coupled with mental health impacts associated with intergenerational and historical trauma, alcohol abuse, suicide, and other impacts (see Key Message 2) (see also Ch. 15: Tribes, KM 2).[209]

Farmworkers are vital to the region, yet they often earn very low wages and face discrimination and workplace hazards. Farmworkers and their families often deal with both chronic and acute health impacts because of the high cost of healthcare and physically demanding work environments. Overall, farmworkers, who are largely immigrant laborers from Mexico, Central America, and South America, face distinct challenges and are more vulnerable due to structural causes that can lead to exploitation, discrimination, and violence.[219] Climate change is projected to exacerbate these existing stressors.

While the Northwest is not typically considered a high-risk area for heat-related illness, heat waves (defined as 5-day, 1-in-10-year events) across the country are projected to increase in frequency and intensity.[3] In the Northwest, nighttime heat waves (defined as 3-day, 1-in-100-year events) have a greater influence on human health than daytime heat waves [220] and have increased in frequency since 1901.[221] These changes are projected to make heat-related illness more common in the future. Farmworkers can be particularly vulnerable to heat-related illness due to occupational exposure (heavy exertion and working outdoors)[210] and to air quality concerns associated with wildfires, yet they often do not seek healthcare because of high costs, language barriers, and fear of deportation.[222] Working conditions, as well as cooling and hydration practices, vary across the region.[223]

In urban environments, economically disadvantaged communities and communities of color live in neighborhoods with the greatest exposure to climate and extreme weather events [224] and are, therefore, disproportionately affected by climate stressors.[225,226] Urban heat islands, worsening air quality,[227] less access to transit, increasing demands for food and energy, and proximity to pollution sites can lead to injury, illness, and loss of life for the urban poor (Key Message 4).[225,228] For instance, in the Northwest, increased risk of heat-related illnesses and deaths has been associated with socioeconomic status, age, race, and occupation (for example, outdoor labor).[156,182,229]

Challenges, Opportunities, and Success Stories for Reducing Risk

Many frontline communities are taking actions that begin to address these challenges. Indigenous peoples and Northwest tribes have demonstrated a high degree of resilience by adapting to changing environmental and social conditions for thousands of years (Ch. 15: Tribes).[124] The strong social networks and connectivity, present in many tribes and Indigenous communities, can reduce vulnerability to climate change (Ch. 15: Tribes, KM 3).[230] Efforts to enhance communication and strengthen network connections between tribes and their partners can be seen across the region.

Box 24.5: Collaborations Can Use Existing Social Cohesion to Build Resilience

Social cohesion, social networks, and other forms of social capital can help communities be more resilient to climate change.[231] The Pacific Northwest Tribal Climate Change Network is a regional collaboration aimed at supporting tribal and Indigenous climate resilience by better understanding and communicating the impacts of climate change on Indigenous peoples, tribal sovereignty, and culture. The Network does this by sharing resources such as case studies, tools, and funding opportunities through the Online Tribal Climate Change Guide (https://tribalclimateguide.uoregon.edu/); bringing together a diverse group of tribes, agencies, and nonprofit and private sector organizations; and discussing key actions and initiatives that are building resilience among tribes in the region.

Figure 24.14: Social cohesion and social networks can help communities adapt to changing climate conditions. One example is the Pacific Northwest Tribal Climate Change Network (https://tribalclimate.uoregon.edu/). The Network provides a forum for tribes to work together and with universities, federal agencies, and private and nonprofit organizations to share information, strengthen connections, and build resilience through events such as the 2017 Tribes and First Nations Climate Summit (http://atnitribes.org/climatechange/events/) hosted by the Tulalip Tribes and co-sponsored by the Affiliated Tribes of Northwest Indians, the North Pacific Landscape Conservation Cooperative, and the Pacific Northwest Tribal Climate Change Project. Photo credit: Peggy Harris, Affiliated Tribes of Northwest Indians.

Acknowledging the risk of heat-related illness for outdoor workers, the state of Washington issued rules requiring employers to make specific changes to job sites during the summer season (from May 1 through September 30). For temperatures above certain thresholds, the employer is required to provide at least one quart of water per employee per hour, relieve employees from duty if they are showing signs of heat-related illness, and provide training for employees and supervisors about heat-related illness.[232]

Economically disadvantaged populations and communities of color often face multiple barriers to participating in public processes where decisions about future climate-related investments are made. Organizations representing these frontline communities have found some success prioritizing leadership development through workshops and training that enable new and emerging voices to be heard in more formal policy settings. Engagement has partly been made possible by providing transportation, childcare, meals, and accessibility and by using a relational worldview and trauma-informed approach to community capacity-building. Cities and counties have also made concerted efforts at the policy level to explicitly acknowledge and address race

and social inequities alongside environmental concerns.[147,228,233,234,235] Example actions include targeting investments in frontline communities and providing job training and employment opportunities that help limit displacement and enhance resilience.[147]

Box 24.6: Community Organizations Empower Frontline Communities

Community-based organizations in the Northwest's two most urban centers, Seattle and Portland, have engaged communities of color to assess priorities for building climate resilience. Our People, Our Planet, Our Power[236] and Tyee Khunamokwst: Leading Together[237] both emphasize that any efforts to build climate resilience will be undermined if low-income people and people of color continue to be displaced. Both community-driven efforts indicate strong support for strategies that reduce emissions and simultaneously build community resilience, such as increasing access to active transportation options and installing green infrastructure within under-resourced communities. The cities of Seattle and Portland have made progress in placing equity more centrally in municipal climate planning. The Portland-Multnomah Climate Action through Equity report[147] documents how these efforts led to a more inclusive and accountable climate action plan, and the Seattle Equity & Environment Agenda[228] articulates current disparities and a commitment to ensuring that people most affected by environmental injustices have a strong voice in finding solutions moving forward.

Emerging Issues

There is an emerging understanding of the importance of not only prioritizing climate change preparedness efforts in frontline communities but also involving and empowering these groups in the decision-making and implementation of climate change plans and actions.

The physical and psychological connections people have with natural resources are complex, and additional research would aid understanding of how changing climate conditions are likely to affect not only those natural resources but also the people who depend on them. How intersecting vulnerabilities, driven by a confluence of climatic, social, and economic factors, will compound and accelerate risks in frontline communities is not yet fully understood (Ch. 17: Complex Systems, KM 1). Additional research would help to measure and evaluate how supporting frontline communities in the implementation of community-identified strategies might improve outcomes and increase not only climate resilience but also equity and economic vitality in the Northwest and across the country.

Box 24.7: 2015—A Prelude of What's to Come?

In 2015, the Northwest experienced its warmest year on record.[238] Severe drought, large wildfires, heat waves (on land and in the ocean), and record harmful algal blooms occurred. An exceptionally warm winter led to record-low mountain snowpack across the region as precipitation fell largely as rain instead of snow.[9] The lack of snowpack and a dry spring led to dry fuel conditions that primed the largest wildfire season recorded in the region.[239]

Extreme climate variability provides a preview of what may be commonplace in the future.

In the Northwest, 2015 temperatures were 3.4°F above normal (as compared to the 1970–1999 average),[238] with winter temperatures 6.2°F above normal.[240] The warm 2015 winter temperatures are illustrative of conditions that may be considered "normal" by mid-century (higher scenario, RCP8.5) or late century (lower scenario, RCP4.5).[11]

Winter, spring, and summer precipitation during 2015 for the Northwest were below normal (as compared to the 1970–1999 average) by 25%, 35%, 14%, respectively (NOAA 2017).[241,242,243] Precipitation from January to June 2015 was the 7th driest on record for the region (4.6 inches below the 20th century average).[244] In general, most climate models project increases in future Northwest winter and spring precipitation with decreases in the summer, although some models project increases and others decreases in each season.[11] The 2015 spring precipitation deficits are similar to the largest decreases (−34%) in summer precipitation projected for the end of the century (2070–2099) under a higher scenario (RCP8.5).[11]

Snowpacks in Oregon and Washington in 2015 were the lowest on record at 89% and 70% below average, respectively.[9] These levels are more extreme than projected under the higher scenario (RCP8.5) by end of century (65% below average).[245] However, with continued warming, this type of low snowpack drought is expected more often. For example, the 2015 extreme low snowpack conditions in the McKenzie River Basin (which sits largely in the middle elevation of the Oregon Cascades) could occur on average about once every 12 years under 3.6°F (2.0°C) of warming.[246] For each 1.8°F (1°C) of warming, peak snow-water equivalent in the Cascades is expected to decline 22%–30%.[247]

What happened? How were systems tested? What vulnerabilities were highlighted?

Impacts from the 2015 "snow drought" were widespread, including irrigation shortages, agricultural losses, limited snow- and water-based recreation, drinking water quality concerns, hydropower shortages, and fish die-offs from impaired stream water quality. Many farmers received a reduced allocation of water, and irrigation water rights holders had their water shut off early; senior water rights holders had their water shut off early for the first time ever.[248] For example, Treasure Valley farmers in eastern Oregon received only a third of their normal irrigation water because the Owyhee Reservoir received inadequate river inflows to fill the reservoir for the third year in a row.[249]

Box 24.7: 2015—A Prelude of What's to Come? *continued*

Agricultural-related impacts of the drought were numerous, including damaged crops, reduced yields, altered livestock management, fewer planted crops, and land left idle (for example, 20% of farm acres in Treasure Valley, Oregon, were left idle).[248] Estimated agricultural economic losses were between $633 million and $773 million in Washington, including losses of over $7.7 million in blueberries, nearly $14 million in red raspberries, $500 million in a selection of 15 crops that make up more than three-quarters of Washington's cultivated acreage, and more than $33 million in the dairy industry (losses reported in 2015 dollars).[250]

Low-elevation ski areas struggled to stay open during the 2014–2015 season. Hoodoo Ski Area in the Oregon Cascades had its shortest season in 77 years of operations after closing for the season in mid-January;[246] Stevens Pass Mountain Resort in Washington's North Cascades only opened for 87 days, down from an average of 150;[251] and Silver Mountain Resort in Idaho closed its ski lifts by the end of March, a month earlier than usual.[252] Summer water recreation also suffered. Visitation at Detroit Lake, a reservoir in the Cascade foothills, decreased by 26% due to historically low water levels—70 feet (21 meters) below reservoir capacity in July—and unusable boat ramps.[246,253]

Low summer stream levels and warm waters, which amplified a naturally occurring fish disease, resulted in widespread fish die-offs across the region, including hundreds of thousands of sockeye salmon in the Columbia and Snake River Basins.[136,248,254] And for the first time ever, Oregon implemented a statewide daily fishing curtailment beginning in July 2015 to limit added stress on the fish from fishing.[248]

The lack of snowpack in 2015 in concert with extreme spring and summer precipitation deficits led to the most severe wildfire season in the Northwest's recorded history with more than 1.6 million acres burned across Oregon and Washington, incurring more than $560 million in fire suppression costs (in 2015 dollars).[239] In Oregon, the cost of large fires in 2015 was 344% of the 10-year average of large-fire costs.[248] The wildfire season resulted in transmission shutdowns for Seattle City Light during the Goodell Fire (see Key Message 3) and infrastructure damage for Idaho Power Company following the Soda Fire.[255] Smoke from the wildfires caused significant air quality and health concerns from late July through September, particularly in eastern Oregon and Washington, Idaho, Colorado, and Canada.[256,257]

The ocean heat wave referred to as "the Blob" was first detected off the Pacific coast in 2013, and by 2014 it spanned the coast from Alaska to California.[10] In 2015, the largest harmful algal bloom recorded on the West Coast was associated with the Blob. High levels of multiple toxins, including domoic acid and paralytic shellfish toxins, closed a wide range of commercial, recreational, and tribal fisheries, including salmon, shellfish, and Dungeness crab along the entire Northwest coast.[172,258,259,260]

Box 24.7: 2015—A Prelude of What's to Come? *continued*

Who is doing what to increase resilience? What success stories are there?

The conditions in 2015 tested the capacity of existing systems and provided insights into potential future adaptation priorities. Several actions to increase resilience have already begun across multiple levels of governance. For example, the Oregon Drought Task Force was created to "review the State's existing drought response tools, identify potential gaps, and make recommendations on tools and information needed to ensure that the State is prepared to respond during a drought in the future."[261] Washington assessed the economic impact on agriculture and recommended developing a plan "to assist growers and plan for a future that will include increased incidence of severe weather events such as the 2015 drought."[250]

At the onset of the drought, anticipated agricultural losses were much higher than what occurred because of actions at the federal and state levels, and actions implemented by the farmers themselves (Box 24.1).[250] This highlights the adaptive capacity of some producers in the agricultural sector (Key Message 1). However, as conditions experienced in 2015 become more regular as a result of climate change, some farms will likely struggle to stay solvent despite adaptation interventions (Ch. 10: Ag & Rural, KM 1).[250]

After the lack of snow during the previous winter season prevented Mount Ashland Ski Area in southwest Oregon from opening at all, the ski area instituted several adaptation strategies that helped it open and stay open during the 2015 busy winter holidays. Strategies included snow-harvesting and thinning vegetation, among others. Future plans include diversifying the business by creating more summer recreation opportunities, so that the ski area's revenue depends less on snow-related recreation.[249]

In the Yakima Basin, irrigators, conservation groups, and state and federal agencies worked together to replenish the diminished tributary flows to bolster the salmon runs and riparian habitat during the drought. Water from the Yakima River was redirected through farm irrigation canals to seven tributaries. Although this further reduced the farmers' irrigation water, they agreed to continue rerouting water to sustain the fish.[262]

Acknowledgments

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Opening Image Credit
Sawtooth National Forest, Idaho. Photo credit: Mark Lisk/USDA Forest Service.

Traceable Accounts

Process Description

This assessment focuses on different aspects of the interaction between humans, the natural environment, and climate change, including reliance on natural resources for livelihoods, the less tangible values of nature, the built environment, health, and frontline communities. Therefore, the author team required a depth and breadth of expertise that went beyond climate change science and included social science, economics, health, tribes and Indigenous people, frontline communities, and climate adaptation, as well as expertise in agriculture, forestry, hydrology, coastal and ocean dynamics, and ecology. Prospective authors were nominated by their respective agencies, universities, organizations, or peers. All prospective authors were interviewed with respect to the qualifications, and selected authors committed to remain part of the team for the duration of chapter development.

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors at workshops, weekly teleconferences, and email exchanges. The author team, along with the U.S. Global Change Research Program (USGCRP), also held stakeholder meetings in Portland and Boise to solicit input and receive feedback on the outline and draft content under consideration. A series of breakout groups during the stakeholder meetings provided invaluable feedback that is directly reflected in how the Key Messages were shaped with respect to Northwest values and the intersection between humans, the natural environment, and climate change. The authors also considered inputs and comments submitted by the public, interested stakeholders, the National Academies of Sciences, Engineering, and Medicine, and federal agencies. For additional information on the overall report process, see Appendix 1: Process. The author team also engaged in targeted consultations during multiple exchanges with contributing authors for other chapters, who provided additional expertise on subsets of the Traceable Accounts associated with each Key Message.

The climate change projections and scenarios used in this assessment have been widely examined and presented elsewhere[11,50,263,264] and are not included in this chapter. Instead, this chapter focuses on the impact of those projections on the natural resources sector that supports livelihoods (agriculture, forestry, fisheries, and outdoor recreation industry), the intangible values provided by the natural environment (wildlife, habitat, tribal cultures and well-being, and outdoor recreation experiences), human support systems (built infrastructure and health), and frontline communities (farmworkers, tribes, and economically disadvantaged urban communities). The literature cited in this chapter is largely specific to the Northwest states: Washington, Oregon, and Idaho. In addition, the authors selected a series of case studies that highlight specific impacts, challenges, adaptation strategies and successes, and collaborations that are bringing communities together to build climate resilience. The most significant case study is the 2015 case study (Box 24.7), which cuts across all five Key Messages and highlights how extreme climate variability that is happening now may become more normal in the future, providing important insights that can help inform and prioritize adaptation efforts.

Key Message 1

Natural Resource Economy

Climate change is already affecting the Northwest's diverse natural resources (*high confidence*), which support sustainable livelihoods; provide a robust foundation for rural, tribal, and Indigenous communities; and strengthen local economies (*high confidence*). Climate change is expected to continue affecting the natural resource sector (*likely, high confidence*), but the economic consequences will depend on future market dynamics, management actions, and adaptation efforts (*very likely, medium confidence*). Proactive management can increase the resilience of many natural resources and their associated economies (*very likely, medium confidence*).

Description of evidence base

Multiple studies suggest that Northwest natural resource sectors will likely be directly affected by climate change, including increased temperatures, changes in precipitation patterns, and reduced snowpack (see NOAA State Climate Summaries for Oregon, Washington, and Idaho).[265,266,267] The direct and indirect consequences of these climate drivers are projected to impact regional natural resource sectors in varied ways. In many cases, the secondary and tertiary effects of climatic changes have larger consequences on the natural resource sector, such as increased insect and pest damage to forests,[41] increased wildfire activity,[8] changes to forage quality and availability for livestock,[38,39,40] reductions in water availability for irrigation and subsequent impacts to water rights,[268,269] and increasing temperatures and ocean acidity limiting the viability of existing commercial and recreational fisheries;[30,55,56,57] lower snowfall is also expected to reduce the economic benefits associated with the recreational skiing industry.[19,58]

There is good evidence that natural resource managers are attempting to build more resilient production systems in the face of climate change through the adoption of adaptation practices (see Box 24.1), particularly those that build soil resources to increase resilience in the face of more extreme and variable weather; however, in some cases not all adaptation strategies will necessarily lead to broader soil benefits.[270,271] There is also evidence that adaptive strategies coupled with increased warming will likely shorten the growing season in some parts of the Northwest due to earlier crop maturation, coupled with earlier plantings, leading to lower irrigation demand during low flow periods.[34] Forest managers are also incorporating adaptation strategies focused on addressing drought and fire risks as well as broader efforts to protect and maintain key forest ecosystem services.[67] While adapting to changing ocean conditions is challenging,[83] some in the industry are improving monitoring and hatchery practices to reduce risks.[82] And some in the outdoor recreation industry are looking for ways to benefit from increased temperatures;[88] for instance, many ski resorts are diversifying their recreational opportunities to take advantage of warmer weather and earlier snowmelt.[272,273]

Yet, how individual actors respond to changes in climate is a source of uncertainty, particularly if these actions do not reduce climate risks or capitalize on potential benefits as expected.[64] Additionally, many adaptive actions, at least in the short term, will likely be costly for individual producers to implement.[37,274]

Major uncertainties

Climate impacts, such as increased temperatures, reduced snowpack, and more variable precipitation and subsequent impacts on pests, disease, fire incidence, and other secondary impacts will very likely indirectly affect livelihoods and the economic viability of natural resource sectors, with more severe impacts to rural, tribal, and Indigenous communities (Ch. 10: Ag & Rural). There is, however, greater uncertainty as to how precisely these impacts are projected to affect natural resource managers' financial security and their subsequent land-use decisions (Ch. 5: Land Changes), as well as other factors important to sustainable livelihoods and community well-being.

This is particularly relevant for key commodities that are integrated with national and international markets that are influenced by multiple factors and are difficult to predict (Ch. 10: Ag & Rural; Ch. 16: International). National and global market dynamics will likely be influenced by broader climate change effects on other natural resource sectors in the United States and across the globe,[50] while also being impacted by a broad array of factors that include technological developments, laws, regulations and policies affecting trade and subsidies, and security issues. There are instances where the economic consequences will likely be positive, particularly in comparison to other regions in the United States, such as found in the dairy production sector.[65] The economic impacts to regional fisheries are much less certain as iconic species and industries in the Northwest struggle to maintain viability.[51,52,53] Although much is being researched with respect to the effects of climate change on forests and associated ecosystem services (e.g., Vose et al. 2016[275]), far less has been explored with respect to timber markets and attendant infrastructure and processing.

Description of confidence and likelihood

There is *high confidence* that climate change, through reductions in snowpack, increased temperatures, and more variable precipitation, is already affecting the Northwest's diverse natural resource base. There is *high confidence* that these natural resource sectors provide critical economic benefits, particularly for rural, tribal, and Indigenous communities who are more dependent on economic activities associated with natural resource management. There is *high confidence* that climate change will have a large impact on the natural resource sector throughout this century; however, there is *medium confidence* that these impacts will negatively impact rural, tribal, and Indigenous livelihoods, particularly about how projected changes will economically impact specific natural resource sectors due to large uncertainties surrounding global market dynamics that are influenced by climatic and non-climatic factors. It is *very likely* that proactive management efforts will be required to reduce climate risks, yet there is *medium confidence* that these adaptation efforts will adequately reduce negative impacts and promote sector-specific economic benefits.

Key Message 2

Natural World and Cultural Heritage

Climate change and extreme events are already endangering the well-being of a wide range of wildlife, fish, and plants (*high confidence*), which are intimately tied to tribal subsistence culture (*very high confidence*) and popular outdoor recreation activities (*high confidence*). Climate change is projected to continue to have adverse impacts on the regional environment (*very likely*), with implications for the values, identity, heritage, cultures, and quality of life of the region's diverse population (*high confidence*). Adaptation and informed management, especially culturally appropriate strategies, will likely increase the resilience of the region's natural capital (*medium confidence*).

Description of evidence base

Since the Third National Climate Assessment, there have been significant contributions within the literature in relation to climate impacts to Northwest communities, with specific focus on how values and activities, such as recreation, iconic wildlife, management, and tribal and Indigenous cultures, will likely be impacted.

Wildlife are projected to have diverse responses to climate change.[94,96,121] Droughts, wildfires, reduced snowpack and persistence, shifted flood timing, and heat stress can cause habitat loss or fragmentation[84] and increase mortality of waterfowl; trout, salmon, and other coldwater fish;[52,98,276,277,278] amphibians; wolverines; lynxes; and snowshoe hares.[94] Other species, such as elk and deer, may benefit from future climate conditions.[96]

Multiple studies also demonstrate that climate change impacts will likely affect other iconic, Northwest species. Wildfires will affect berries, roots, and plants;[85,105] ocean acidification is increasing shellfish mortality, and ocean acidification and warmer ocean temperatures are altering marine food webs;[279,280,281] and aquatic acidification is affecting salmon physiology and behavior.[282] These impacts are project to have direct negative impacts on traditional Sacred First Foods.[85,86] Droughts and reduced snowpack will also reduce tribal water supplies.[101,283] The loss of these First Foods is projected to have cascading physical health impacts, such as diabetes,[125] and mental health impacts.[124,125,189,209,214]

Salmon is one of the most iconic Northwest species and important First Foods for Tribes. Salmon are at high risk to climate change because of decreasing summer flows due to changes in seasonal precipitation and reduced snowpack,[284,285,286,287,288] habitat loss through increasing storm intensity and flooding,[100,287] physiological and behavioral sensitivity and increasing mortality due to warmer stream and ocean temperatures, and cascading food web effects due to ocean acidification.[29,281,289,290] These impacts can be amplified due to human-placed impediments (culverts, dams), contaminants, and diseases.[291,292,293]

There are multiple lines of evidence verifying that reduced snowfall and snowpack in the future will adversely impact winter and snow-based recreation, including a reduction in ski visitation rates.[19,58,91] This will also adversely affect summer water-based recreation such as boating and rafting,[277] although warmer temperatures in the future can increase demand for water-based

recreation and visitations rates to parks.[88,89,90] Future habitat shifts in marine species[51] and warmer ocean temperatures are projected to lead to declines in opportunities for ocean fishing recreation.[55,56,57,294] Ocean acidification and harmful algal blooms are also projected to reduce recreational shellfish gathering.[55] Increased wildfire frequency[8] will reduce air quality, and some evidence suggests that this can reduce outdoor recreation opportunities and enjoyment. Regional case studies highlight climate impacts to snow-based recreation, ocean fishing, water-based recreation, and decreased air quality.[28,53,276]

Adaptation and management strategies in response to climate impacts on the natural capital and Northwest heritage are extremely varied across the region. Many tribes have begun managing First Foods and other important cultural resources through climate change vulnerability assessments and adaptation plans that incorporate both traditional knowledge and western science.[85,107,109,112,113,123] Efforts to manage wildlife, habitats, and species are variable in their approaches to increasing climate resilience, with limited uncertainty in how these strategies can collectively result in increased climate resilience of the region's natural capital.[54,110,114,117,118,119,120]

Major uncertainties

There is strong evidence to suggest that recreational opportunities are an important quality of the Northwest,[87] but there is uncertainty around the perceived importance of future recreation opportunities' prioritization in people's quality of life despite the direct reduction of many recreational opportunities.[127]

The effects of climate change on game species are uncertain, with large potential forcing in both directions and a lack of information on which processes will dominate consequences for game species and how managers might be able to effectively adapt to changing climate.

Description of confidence and likelihood

There is *high confidence* that climate change and extreme events have already endangered the well-being of a wide range of wildlife, fish, and plants. There is *very high confidence* that these impacts will directly threaten tribal subsistence and culture and *high confidence* that these impacts will threaten popular recreation activities. Future climate change will *very likely* continue to have adverse impacts on the regional environment. There is *high confidence* that future climate change will have negative impacts on the values, identity, heritage, cultures, and quality of life of the diverse population of Northwest residents. There is *medium confidence* that adaptation and informed management, especially culturally appropriate strategies, will increase the resilience of the region's natural capital.

Key Message 3

Infrastructure

Existing water, transportation, and energy infrastructure already face challenges from flooding, landslides, drought, wildfire, and heat waves (*very high confidence*). Climate change is projected to increase the risks from many of these extreme events, potentially compromising the reliability of water supplies, hydropower, and transportation across the region (*likely, high confidence*). Isolated communities and those with systems that lack redundancy are the most vulnerable (*likely, medium confidence*). Adaptation strategies that address more than one sector, or are coupled with social and environmental co-benefits, can increase resilience (*high confidence*).

Description of evidence base

There is a growing body of evidence suggesting that climate change will likely increase the frequency and/or intensity of extreme events such as flooding, landslides, drought, wildfire, and heat waves.[27,139,142,295,296,297,298,299,300,301,302] Several investigations have highlighted the vulnerability of water supply, hydropower, and transportation to such changes.[33,139,303,304,305,306,307]

Infrastructure redundancy is widely accepted as a means to enhance system reliability. Multiple investigations cite the importance of system redundancy for transportation, energy, and water supply.[136,146,308] Several studies describe the ways that agencies tasked with water, energy, and transportation management are exploring climate change impacts and potential adaptation options.[133,146,148,151,309,310,311,312,313,314]

Major uncertainties

Many analyses and anecdotal evidence link the risk of infrastructure disruption or failure to extreme events. However, the attribution of specific infrastructure impacts to climate variability or climate change remains a challenge. In many cases, infrastructure is subject to multiple climate and non-climate stressors. Non-climate stressors common to many parts of the region include increases in demand or usage from growing populations and changes in land use or development. In addition, much infrastructure across the region is beyond its useful lifetime or may not be in a state of good repair. These factors typically enhance sensitivity to many types of stressors but add uncertainty when trying to draw a direct connection between climate and infrastructure impacts.

Demographic shifts remain an important uncertainty when assessing future infrastructure impacts as well as the relative importance of certain types of infrastructure. Migration to and within the region can fluctuate on timescales shorter than those of climate change. As people move, the relative importance of different types of infrastructure are likely to change, as are the consequences of impacts.

Lastly, there is considerable uncertainty in quantitatively assessing the role of redundancy in minimizing or managing impacts. Metrics for determining the extent to which networking or emergency/backup systems yield adaptive capacity are not currently available at the regional scale.

Description of confidence and likelihood

There is *very high confidence* in the link between extreme events and infrastructure impacts. Most of the existing vulnerability assessments in this region, as well as those at larger spatial scales, emphasize extreme events as a key driver of past impacts. Most infrastructure is planned and designed to withstand events of a specified frequency and magnitude (for example, the 100-year flood, design storms), underscoring the importance of extreme events to our assumptions about infrastructure reliability and function. There is *high confidence* that rising temperatures, increases in heavy rainfall, and hydrologic changes are projected for the region.[5,71,139] These changes are anticipated to raise the risk of flooding, landslides, drought, wildfire, and heat waves. There is *medium confidence* about the role of redundancy in determining vulnerability. Although this link has been exhibited in many case studies, quantitative evidence at the local and regional scale has yet to be developed.

Impacts discussed in this chapter (e.g., WSDOT 2014, ODOT and OHA 2016, Withycomb 2017, US Climate Resilience Toolkit 2017[129,130,132,135]), within other chapters (see Ch. 11: Urban; Ch. 12: Transportation; Ch. 17: Complex Systems; Ch. 28: Adaptation), and elsewhere[139] highlight the connections among infrastructure systems, or between infrastructure reliability, and access to critical services. In addition, infrastructure systems are faced with a host of non-climate stressors (for example, increased demands from growing population, land-use change). As a result, there is *high confidence* that adaptation efforts designed to address climate impacts across multiple sectors (e.g., Portland-Multnomah County 2014, 2016[146,147]), as well as those that will yield social environmental co-benefits, will build resilience.

Key Message 4

Health

Organizations and volunteers that make up the Northwest's social safety net are already stretched thin with current demands (*very likely, high confidence*). Healthcare and social systems will likely be further challenged with the increasing frequency of acute events, or when cascading events occur (*very likely, high confidence*). In addition to an increased likelihood of hazards and epidemics, disruptions in local economies and food systems are projected to result in more chronic health risks (*very likely, medium confidence*). The potential health co-benefits of future climate mitigation investments could help to counterbalance these risks (*likely, medium confidence*).

Description of evidence base

Cascading hazards could occur in any season; however, the summer months pose the biggest health challenges. For example, wildfire could occur at the same time as extreme heat and could damage electrical distribution systems, thereby simultaneously exposing people to smoke and high temperatures without the ability to pump water, filter air, or control indoor temperatures. Although some work is being done to prepare, responses to emergency incidents continue to show that there are considerable gaps in our medical and public health systems.[315] Public health departments are in place to track, monitor, predict, and develop response tactics to disease outbreaks or other health threats. In the case of cascading hazards, the public health system has a

role in communicating risks to the public as well as strategies for self-care and sheltering-in-place during a crisis. Unfortunately, local health departments report inadequate capacity to respond to local climate change-related health threats, mainly due to budget constraints.[316] Hospitals in the United States routinely operate at or above capacity. Large numbers of emergency rooms are crowded with admitted patients awaiting placement in inpatient beds, and hospitals are diverting more than half a million ambulances per year due to emergency room overcrowding.[317]

Existing environmental health risks are expected to be exacerbated by future climate conditions,[187] yet over 95% of local health departments in Oregon reported having only partial-to-minimal ability to identify and address environmental health hazards.[194] The capacity of our public health systems is largely inadequate and unable to meet basic responsibilities to protect the health and safety of people in the Northwest.[162,194] Public health leaders from state and local health authorities, state advisory boards, and public health associations have been working together for over five years to develop a plan for rebuilding, modernizing, and funding the region's public health systems.

Socioeconomic income levels can be a predictor of environmental health outcomes in the future.[187,195] Food systems face continued increases in environmental pressures, with climate change influencing both the quality of food and the ability to distribute it equitably. The capacity to ensure food security in the face of rapidly changing climate conditions will likely be a major determinant of disease burden.[318]

Climate mitigation strategies can in some cases have substantial health co-benefits, with evidence pointing toward active transportation[319] and green infrastructure improvements.[320] This evidence of health co-benefits provides an additional and immediate rationale for reductions in greenhouse gas emissions beyond that of climate change mitigation alone. Recognition that mitigation strategies can have substantial benefits for both health and climate protection offers the possibility of strategies that are potentially both more cost effective and socially attractive than are those that address these priorities independently.[321] The Oregon Health Authority's Climate Smart Strategy Health Impact Assessment found that almost all climate mitigation policies under consideration by the Metro Regional Government could improve health, and that certain policy combinations were more beneficial, namely those that reduced vehicle miles traveled.[322] For example, according to 2009 data available on the National Environmental Public Health Tracking Network, a 10% reduction in $PM_{2.5}$ could prevent more than 400 deaths per year in a highly populated county and about 1,500 deaths every year in the state of California alone. Working across sectors to incorporate a health promotion approach in the design and development of built environment components could mitigate climate change, promote adaptation, and improve public health.[323]

Major uncertainties

Preparing and responding to cascading hazards is complex and involves many organizations outside of the medical and public health systems. There is not a common set of metrics or standards for measuring surge capacity and emergency preparedness across the region.

There is uncertainty in whether domestic migration will place further stress on social safety net systems.

Description of confidence and likelihood

There is *high confidence* that there will be increased hazards and epidemics, which will *very likely* disrupt local economies, food systems, and exacerbate chronic health risks, especially among populations most at risk. There is *high confidence* that these acute hazards will increase due to future climate conditions and will *very likely* increase the demand on organizations and volunteers that respond and form the region's social safety net. There is *medium confidence* that mitigation investments can help counterbalance these risks and *likely* result in health co-benefits for the region.

Key Message 5

Frontline Communities

Communities on the front lines of climate change experience the first, and often the worst, effects. Frontline communities in the Northwest include tribes and Indigenous peoples, those most dependent on natural resources for their livelihoods, and the economically disadvantaged (*very high confidence*). These communities generally prioritize basic needs, such as shelter, food, and transportation (*high confidence*); frequently lack economic and political capital; and have fewer resources to prepare for and cope with climate disruptions (*very likely, very high confidence*). The social and cultural cohesion inherent in many of these communities provides a foundation for building community capacity and increasing resilience (*likely, medium confidence*).

Description of evidence base

Multiple lines of research have shown that the impacts of extreme weather events and climate change depend not only on the climate exposures but also on the sensitivity and adaptive capacity of the communities being exposed to those changes.[187,230,324,325] For frontline communities in the Northwest, it is the interconnected nature of legacy exposure, enhanced exposure, higher sensitivity, and less capability to adapt that intensifies a community's climate vulnerability.[187,216]

There are multiple lines of evidence that demonstrate that tribes and Indigenous peoples are particularly vulnerable to climate change. Climate stressors, such as sea level rise, ocean acidification, warmer ocean and stream temperatures, wildfires, or droughts, are projected to disproportionately affect tribal and Indigenous well-being and health,[106,187,326,327] economies,[85,124] and cultures.[105,106] These losses can affect mental health and, in some cases, trigger multigenerational trauma.[125,189,209,214]

There is limited research on how climate change is projected to impact farmworkers, yet evidence suggests that occupational health concerns, including heat-related concerns[210,223] and pesticide exposure,[328] could increase, thus exacerbating health and safety concerns among economically and politically marginalized farmworker communities.

Particularly relevant to economically disadvantaged urban populations, extensive work has been done evaluating and analyzing social vulnerability[211] and applying that work to the Northwest.[195] There has also been work completed considering both relative social vulnerability and environmental health data (see WSDOH 2018[162]).

Strong evidence through reports and case studies demonstrates that tribes are active in increasing their resilience through climate change vulnerability assessments and adaptation plans (see https://

www.indianaffairs.gov/WhoWeAre/BIA/climatechange/Resources/Tribes/index.htm and http://tribalclimateguide.uoregon.edu/adaptation-plans for a list of tribal and Indigenous climate resilience programs, reports, and actions) and through regional networks (for example, Pacific Northwest Tribal Climate Change Network, Affiliated Tribes of Northwest Indians, Northwest Indian Fisheries Commission, Columbia River Inter-Tribal Fish Commission, Point No Point Treaty Council, Upper Snake River Tribes Foundation).

There are also many community organizations across the region focusing on engaging, involving, and empowering frontline communities, including communities of color, immigrants, tribes and Indigenous peoples, and others to design plans and policies that are meaningful (for example, Front and Centered, Got Green, Puget Sound Sage, Coalition of Communities of Color).

Major uncertainties

Actual climate change related vulnerabilities will vary by community and neighborhood.[187,208] Therefore, the scale of any vulnerability assessment or adaptation plan will matter greatly in assessing the uncertainties.

The secondary and tertiary impacts of changing climate conditions are less well understood. For example, climate change may increase the amount and frequency of pesticides used, and the variety of products used to manage crop diseases, pests, and competing weeds.[328] This is likely to increase farmworker exposure to pesticides and ultimately affect their health and well-being. Further, it is unclear how the altered timing of agricultural management of key crops across the United States (for example, the timing of cherry picking) due to increased temperatures and altered growing seasons may influence the demand for farmworker labor, particularly migrant labor, and how this might impact their livelihoods and occupational health.

There is emerging evidence that there are overlaps between environmental justice concerns and climate change impacts on these communities,[233,237] and that solutions designed to address one issue can provide effective solutions for the other issue if done well.[147]

No systematic catalogue of the actions and efforts of frontline communities in the region to address their climate-related challenges exists. Thus, at this point, most examples of adaptation and climate preparedness are anecdotal, but these examples suggest an increasing trend to link adaptation efforts that simultaneously address both climate and equity concerns. However, this approach is still used sporadically based on the interests, needs, and resources of the communities.

Description of confidence and likelihood

There is *very high confidence* that frontline communities are the first to be affected by the impacts of climate change. Due to their enhanced sensitivity to changing conditions, direct reliance on natural resources, place-based limits, and lack of financial and political capital, it is *very likely* that they will face the biggest climate challenges in the region. However, there is a significant amount of uncertainty in how individuals and individual communities will respond to these changing conditions, and responses will likely differ between states, communities, and even neighborhoods. Thus, it is the complex interaction between the climate exposures and the integrated social-ecological systems as well as the surrounding policy and response environment that will ultimately determine the challenges these communities face.

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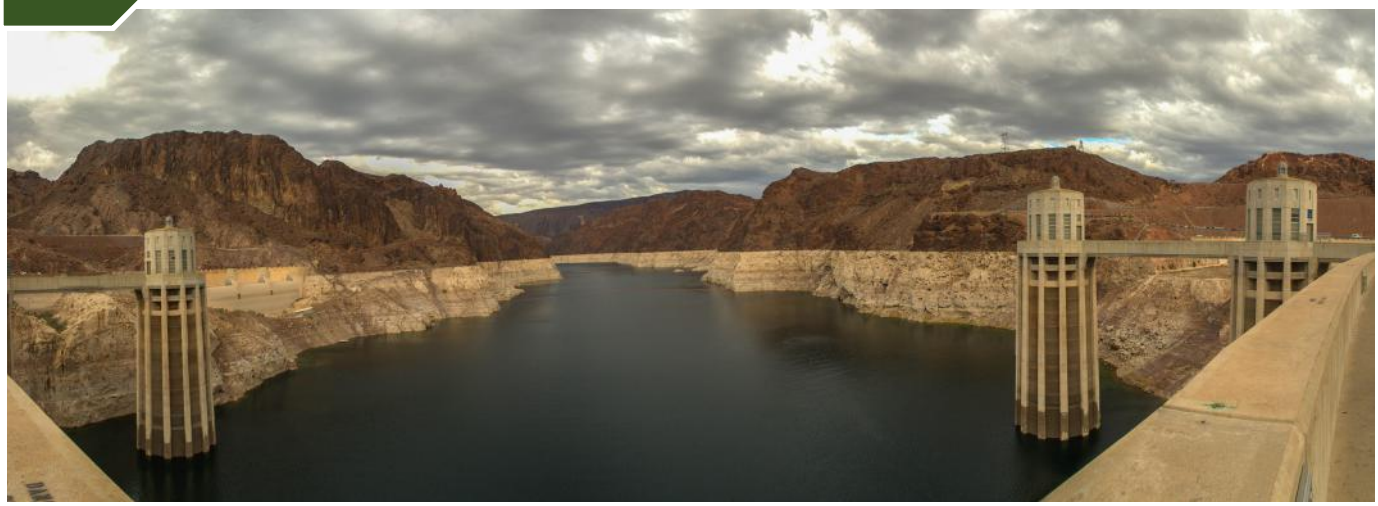
25 Southwest



Low water levels in Lake Mead

Key Message 1

Water Resources

Water for people and nature in the Southwest has declined during droughts, due in part to human-caused climate change. Intensifying droughts and occasional large floods, combined with critical water demands from a growing population, deteriorating infrastructure, and groundwater depletion, suggest the need for flexible water management techniques that address changing risks over time, balancing declining supplies with greater demands.

Key Message 2

Ecosystems and Ecosystem Services

The integrity of Southwest forests and other ecosystems and their ability to provide natural habitat, clean water, and economic livelihoods have declined as a result of recent droughts and wildfire due in part to human-caused climate change. Greenhouse gas emissions reductions, fire management, and other actions can help reduce future vulnerabilities of ecosystems and human well-being.

Key Message 3

The Coast

Many coastal resources in the Southwest have been affected by sea level rise, ocean warming, and reduced ocean oxygen—all impacts of human-caused climate change—and ocean acidification resulting from human emissions of carbon dioxide. Homes and other coastal infrastructure, marine flora and fauna, and people who depend on coastal resources face increased risks under continued climate change.

Key Message 4

Indigenous Peoples

Traditional foods, natural resource-based livelihoods, cultural resources, and spiritual well-being of Indigenous peoples in the Southwest are increasingly affected by drought, wildfire, and changing ocean conditions. Because future changes would further disrupt the ecosystems on which Indigenous peoples depend, tribes are implementing adaptation measures and emissions reduction actions.

Key Message 5

Energy

The ability of hydropower and fossil fuel electricity generation to meet growing energy use in the Southwest is decreasing as a result of drought and rising temperatures. Many renewable energy sources offer increased electricity reliability, lower water intensity of energy generation, reduced greenhouse gas emissions, and new economic opportunities.

Key Message 6

Food

Food production in the Southwest is vulnerable to water shortages. Increased drought, heat waves, and reduction of winter chill hours can harm crops and livestock; exacerbate competition for water among agriculture, energy generation, and municipal uses; and increase future food insecurity.

Key Message 7

Human Health

Heat-associated deaths and illnesses, vulnerabilities to chronic disease, and other health risks to people in the Southwest result from increases in extreme heat, poor air quality, and conditions that foster pathogen growth and spread. Improving public health systems, community infrastructure, and personal health can reduce serious health risks under future climate change.

Executive Summary

The Southwest region encompasses diverse ecosystems, cultures, and economies, reflecting a broad range of climate conditions, including the hottest and driest climate in the United States. Water for people and nature in the Southwest region has declined during droughts, due in part to human-caused climate change. Higher temperatures intensified the recent severe drought in California and are amplifying drought in the Colorado River Basin. Since 2000, Lake Mead on the Colorado River has fallen 130 feet (40 m) and lost 60% of its volume, a result of the ongoing Colorado River Basin drought and continued water withdrawals by cities and agriculture.

The reduction of water volume in both Lake Powell and Lake Mead increases the risk of water shortages across much of the Southwest. Local water utilities, the governments of seven U.S. states, and the federal governments of the United States and Mexico have voluntarily developed and implemented solutions to minimize the possibility of water shortages for cities, farms, and ecosystems. In response to the recent California drought, the state implemented a water conservation plan in 2014 that set allocations for water utilities and major users and banned wasteful practices. As a result, the people of the state reduced water use 25% from 2014 to 2017.

Exposure to hotter temperatures and heat waves already leads to heat-associated deaths in Arizona and California. Mortality risk during a heat wave is amplified on days with high levels of ground-level ozone or particulate air pollution. Given the proportion of the U.S. population in the Southwest region, a disproportionate number of West Nile virus, plague, hantavirus pulmonary syndrome, and Valley fever cases occur in the region.

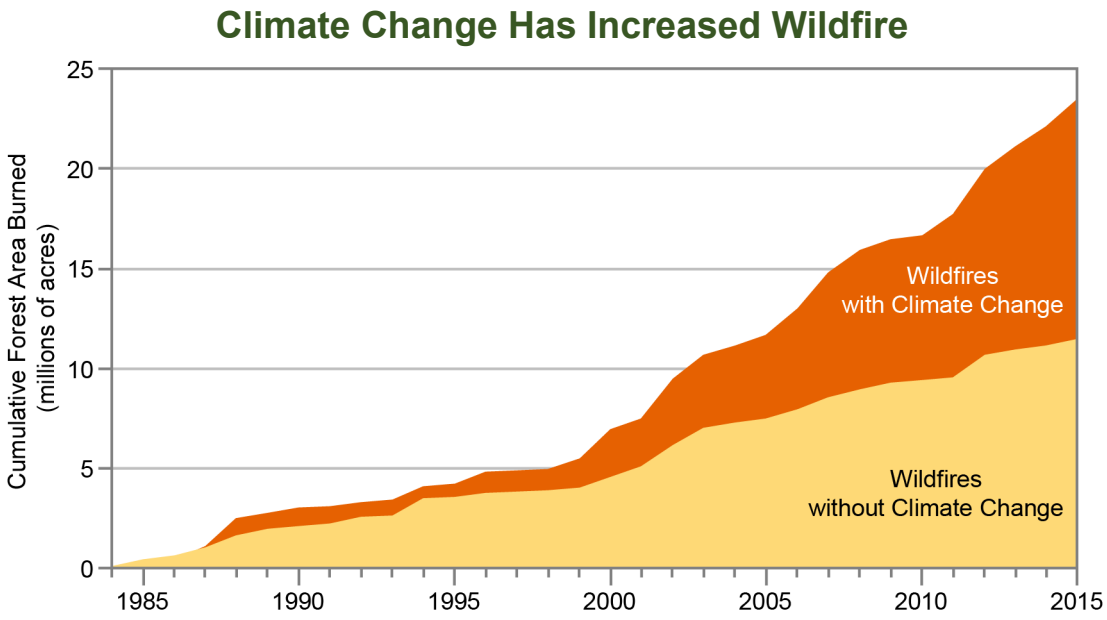
Analyses estimated that the area burned by wildfire across the western United States from 1984 to 2015 was twice what would have burned had climate change not occurred. Wildfires around Los Angeles from 1990 to 2009 caused $3.1 billion in damages (unadjusted for inflation). Tree death in mid-elevation conifer forests doubled from 1955 to 2007 due, in part, to climate change. Allowing naturally ignited fires to burn in wilderness areas and preemptively setting low-severity prescribed burns in areas of unnatural fuel accumulations can reduce the risk of high-severity fires under climate change. Reducing greenhouse gas emissions globally can also reduce ecological vulnerabilities.

At the Golden Gate Bridge in San Francisco, sea level rose 9 inches (22 cm) between 1854 and 2016. Climate change caused most of this rise by melting of land ice and thermal expansion of ocean water. Local governments on the California coast are using projections of sea level rise to develop plans to reduce future risks. Ocean water acidity off the coast of California increased 25% to 40% (decreases of 0.10 to 0.15 pH units) from the preindustrial era (circa 1750) to 2014 due to increasing concentrations of atmospheric carbon dioxide from human activities. The marine heat wave along the Pacific Coast from 2014 to 2016 occurred due to a combination of natural factors and climate change. The event led to the mass stranding of sick and starving birds and sea lions, and shifts of red crabs and tuna into the region. The ecosystem disruptions contributed to closures of commercially important fisheries.

Agricultural irrigation accounts for approximately three-quarters of water use in the Southwest region, which grows half of the fruits, vegetables, and nuts and most of the wine grapes, strawberries, and lettuce for the United States. Increasing heat stress during specific phases of the plant life cycle can increase crop failures.

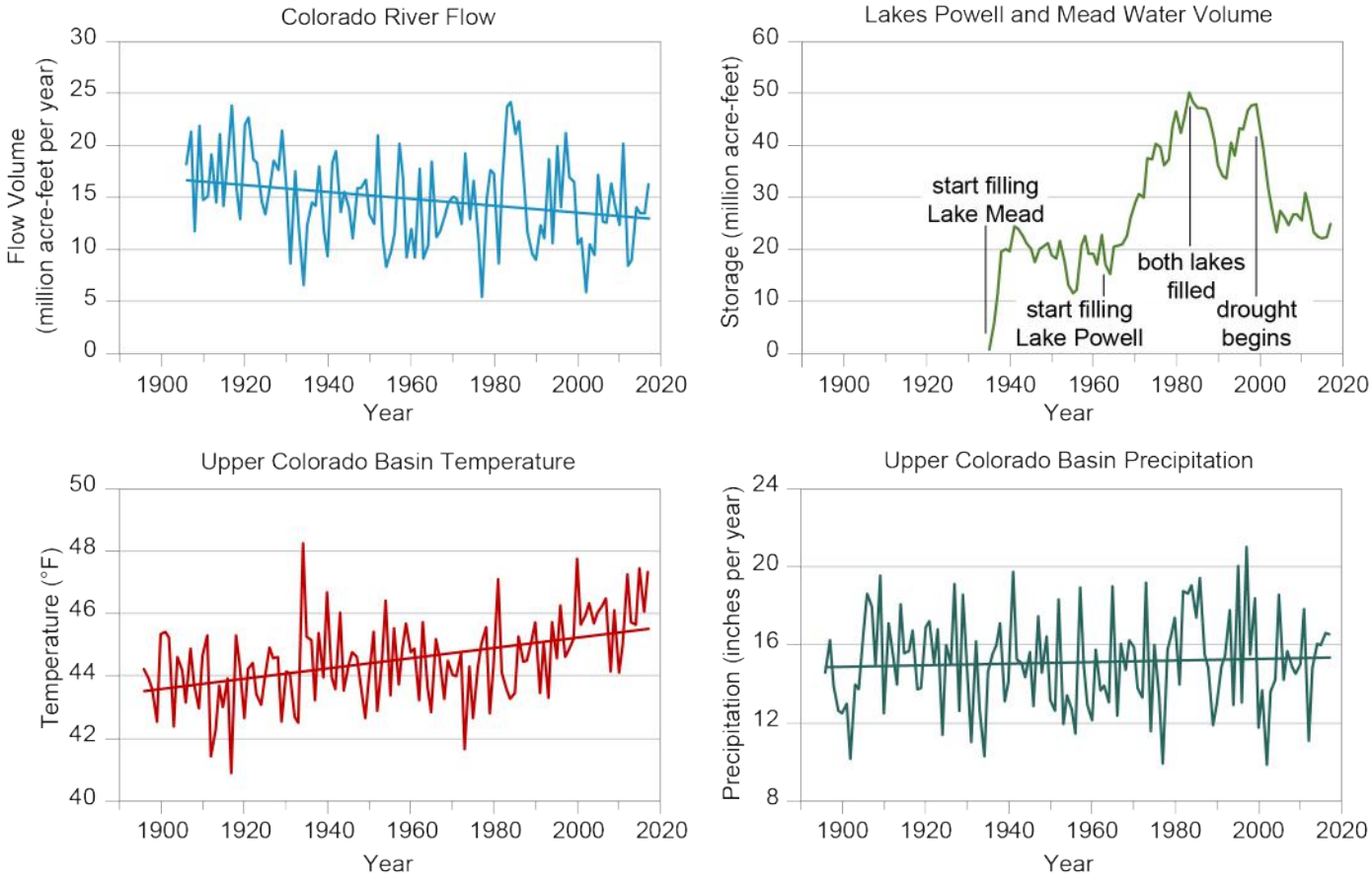
Drought and increasing heat intensify the arid conditions of reservations where the United States restricted some tribal nations in the Southwest region to the driest portions of their traditional homelands. In response to climate change, Indigenous peoples in the region are developing new adaptation and mitigation actions.

The severe drought in California, intensified by climate change, reduced hydroelectric generation two-thirds from 2011 to 2015. The efficiency of all water-cooled electric power plants that burn fuel depends on the temperature of the external cooling water, so climate change could reduce energy efficiency up to 15% across the Southwest by 2050. Solar, wind, and other renewable energy sources, except biofuels, emit less carbon and require less water than fossil fuel energy. Economic conditions and technological innovations have lowered renewable energy costs and increased renewable energy generation in the Southwest.



The cumulative forest area burned by wildfires has greatly increased between 1984 and 2015, with analyses estimating that the area burned by wildfire across the western United States over that period was twice what would have burned had climate change not occurred. *From Figure 25.4 (Source: adapted from Abatzoglou and Williams 2016).*

Severe Drought Reduces Water Supplies in the Southwest



Since 2000, drought that was intensified by long-term trends of higher temperatures due to climate change has reduced the flow in the Colorado River (top left), which in turn has reduced the combined contents of Lakes Powell and Mead to the lowest level since both lakes were first filled (top right). In the Upper Colorado River Basin that feeds the reservoirs, temperatures have increased (bottom left), which increases plant water use and evaporation, reducing lake inflows and contents. Although annual precipitation (bottom right) has been variable without a long-term trend, there has been a recent decline in precipitation that exacerbates the drought. Combined with increased Lower Basin water consumption that began in the 1990s, these trends explain the recently reduced reservoir contents. Straight lines indicate trends for temperature, precipitation, and river flow. The trends for temperature and river flow are statistically significant. *From Figure 25.3 (Sources: Colorado State University and CICS-NC. Temperature and precipitation data from: PRISM Climate Group, Oregon State University,* http://prism.oregonstate.edu*, accessed 20 June 2018).*

Background

The Southwest region encompasses diverse ecosystems, cultures, and economies, reflecting a broad range of climate conditions, including the hottest and driest climate in the United States. Arizona, California, Colorado, New Mexico, Nevada, and Utah occupy one-fifth of U.S. land area, extending across globally unique ecosystems from the Sonoran Desert to the Sierra Nevada to the Pacific Coast. The region is home to 60 million people, with 9 out of 10 living in urban areas and the total population growing 30% faster than the national average.[1] The Nation depends on the region for more than half of its specialty crops such as fruits, nuts, and vegetables.[2] The Southwest also drives the U.S. technology sector, with more than 80% of the country's technology capitalization located in California.[3]

Ecosystems in the Southwest gradually transform from deserts and grasslands in hotter and lower elevations in the south to forests and alpine meadows in cooler, higher elevations in the north. Natural and human-caused wildfire shapes the forests and shrublands that cover one-quarter and one-half of the region, respectively.[4] To conserve habitat for plants and wildlife and supply clean water, timber, recreation, and other services for people, the U.S. Government manages national parks and other public lands covering half of the Southwest region.[5] Climate change is altering ecosystems and their services through major vegetation shifts[213] and increases in the area burned by wildfire.[7]

The California coast extends 3,400 miles (5,500 km),[8] with 200,000 people living 3 feet (0.9 m) or less above sea level.[9] The seaports of Long Beach and Oakland, several international airports, many homes, and high-value infrastructure lie along the coast. In addition, much of the Sacramento–San Joaquin River Delta is near sea level. California has the most valuable ocean-based economy in the country, employing over half a million people and generating $20 billion in wages and $42 billion in economic production in 2014.[10] Coastal wetlands buffer against storms, protect water quality, provide habitat for plants and wildlife, and supply nutrients to fisheries. Sea level rise, storm surges, ocean warming, and ocean acidification are altering the coastal shoreline and ecosystems.

Water resources can be scarce because of the arid conditions of much of the Southwest and the large water demands of agriculture, energy, and cities. Winter snowpack in the Rocky Mountains, Sierra Nevada, and other mountain ranges provides a major portion of the surface water on which the region depends. Spring snowmelt flows into the Colorado, Rio Grande, Sacramento, and other major rivers, where dams capture the flow in reservoirs and canals and pipelines transport the water long distances. Complex water laws govern allocation among states, tribes, cities, ecosystems, energy generators, farms, and fisheries, and between the United States and Mexico. Water supplies change with year-to-year variability in precipitation and water use, but increased evapotranspiration due to higher temperatures reduces the effectiveness of precipitation in replenishing soil moisture and surface water.[11,12,13,14]

Agricultural irrigation accounts for nearly three-quarters of water use in the Southwest region,[15,16] which grows half of the fruits, vegetables, and nuts[2] and most of the wine grapes, strawberries, and lettuce[17] for the United States. Consequently, drought and competing water demands in this region pose a major risk for agriculture and food security in the country. Through production and trade networks, impacts to regional crop production

can propagate nationally and internationally (see Ch. 16: International, KM 1)[18]

Parts of the Southwest reach the hottest temperatures on Earth, with the world record high of 134°F (57°C) recorded in Death Valley National Park, California[19] and daily maximum temperatures across much of the region regularly exceeding 98°F (35°C) during summer.[20] Greenhouse gases emitted from human activities have increased global average temperature since 1880[21] and caused detectable warming in the western United States since 1901.[22] The average annual temperature of the Southwest increased 1.6°F (0.9°C) between 1901 and 2016 (Figure 25.1).[23] Moreover, the region recorded more warm nights and fewer cold nights between 1990 and 2016),[24] including an increase of 4.1°F (2.3°C) for the coldest day of the year. Parts of the Southwest recorded the highest temperatures since 1895, in 2012,[25] 2014,[26] 2015,[27] 2016,[28] and 2017.[29]

Extreme heat episodes in much of the region disproportionately threaten the health and well-being of individuals and populations who are especially vulnerable (Ch. 14: Human Health, KM 1).[30] Vulnerability arises from numerous factors individually or in combination, including physical susceptibility (for example, young children and older adults), excessive exposure to heat (such as during heat waves), and socioeconomic factors that influence susceptibility and exposure (for example, hot and poorly ventilated homes or lack of access to public emergency cooling centers).[31,32,33] Communicable diseases, ground-level ozone air pollution, dust storms, and allergens can combine with temperature and precipitation extremes to generate multiple disease burdens (an indicator of the impact of a health problem).

Episodes of extreme heat can affect transportation by reducing the ability of commercial airlines to gain sufficient lift for takeoff at major regional airports (Ch. 12: Transportation, KM 1).[34]

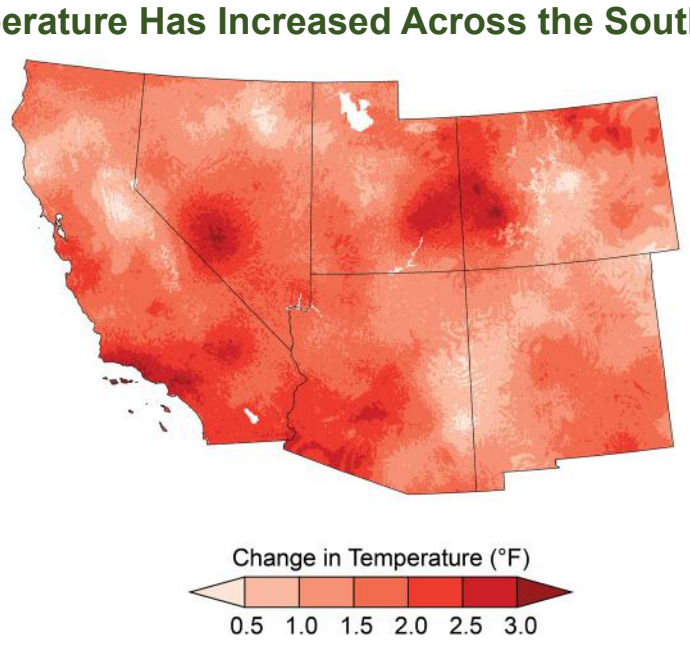


Figure 25.1: Temperatures increased across almost all of the Southwest region from 1901 to 2016, with the greatest increases in southern California and western Colorado.[23] This map shows the difference between 1986–2016 average temperature and 1901–1960 average temperature.[23] Source: adapted from Vose et al. 2017.[23]

Native Americans are among the most at risk from climate change, often experiencing the worst effects because of higher exposure, higher sensitivity, and lower adaptive capacity for historical, socioeconomic, and ecological reasons. With one and a half million Native Americans,[35] 182 federally recognized tribes,[36] and many state-recognized and other non-federally recognized tribes, the Southwest has the largest population of Indigenous peoples in the country. Over the last five centuries, many Indigenous peoples in the Southwest have either been forcibly restricted to lands with limited water and resources[37,38,39] or struggled to get their federally reserved water rights recognized by other users.[40] Climate change exacerbates this historical legacy because the sovereign lands on which many Indigenous peoples live are becoming increasingly dry.

Further, climate change affects traditional plant and animal species, sacred places, traditional building materials, and other material cultural heritage. The physical, mental, emotional, and spiritual health and overall well-being of Indigenous peoples rely on these vulnerable species and materials for their livelihoods, subsistence, cultural practices, ceremonies, and traditions.[41,42,43,44]

In parts of the region, hotter temperatures have already contributed to reductions of seasonal maximum snowpack and its water content over the past 30–65 years,[45,46,47,48,49] partially attributed to human-caused climate change.[45,46,48,49] Increased temperatures most strongly affect snowpack water content, snowmelt timing, and the fraction of precipitation falling as snow.[48,50,51,52,53,54]

The increase in heat and reduction of snow under climate change have amplified recent hydrological droughts (severe shortages of water) in California,[14,55,56,57,58] the Colorado River Basin,[12,13,59] and the Rio Grande.[45,60] Snow droughts can arise from a lack of precipitation (dry snow drought), temperatures that are too warm for snow (warm snow drought), or a combination of the two.[48,51]

Periods of low precipitation from natural variations in the climate system are the primary cause of major hydrological droughts in the Southwest region,[61,62,63,64,65,66,67,68] with increasing temperatures from climate change amplifying recent hydrological droughts, particularly in California and the upper Colorado River Basin.[12,13,14,56,57,59]

Under the higher scenario (RCP8.5), climate models project an 8.6°F (4.8°C) increase in Southwest regional annual average temperature by 2100.[23] Southern parts of the region could get up to 45 more days each year with maximum temperatures of 90°F (32°C) or higher.[23] Projected hotter temperatures increase probabilities of decadal to multi-decadal megadroughts,[61,62,69,70] which are persistent droughts lasting longer than a decade,[69] even when precipitation increases. Under the higher scenario (RCP8.5), much of the mountain area in California with winters currently dominated by snow would begin to receive more precipitation as rain and then only rain by 2050.[71] Colder and higher areas in the intermountain West would also receive more rain in the fall and spring but continue to receive snow in the winter at the highest elevations.[71]

Increases in temperature would also contribute to aridification (a potentially permanent change to a drier environment) in much of the Southwest, through increased evapotranspiration,[69,70,72,73] lower soil moisture,[74] reduced snow cover,[71,75,76,77] earlier and slower snowmelt,[75] and changes in the timing and efficiency of snowmelt and runoff.[50,54,75,76,78,79] Some research indicates increasing frequency of dry high-pressure weather systems associated with changes in Northern Hemisphere

atmospheric circulation.[80,81] These changes would tend to increase the duration and severity of droughts[67,74] and generate an overall drier regional climate.[69,70,72]

Climate models project an increase in the frequency of heavy downpours, especially through atmospheric rivers,[74,82] which are narrow bands of highly concentrated storms that move in from the Pacific Ocean. A series of strong atmospheric rivers caused extreme flooding in California in 2016 and 2017. Under the higher scenario (RCP8.5), models project increases in the frequency and intensity of atmospheric rivers.[83,84,85,86] Climate models also project an increase in daily extreme summer precipitation in the Southwest region, based on projected increases in water vapor resulting from higher temperatures.[20,87,88] Projections of summer total precipitation are uncertain, with average projected totals not differing substantially from what would be expected due to natural variations in climate.[88]

The Southwest generates one-eighth of U.S. energy, with hydropower, solar, wind, and other renewable sources supplying one-fifth of regional energy generation.[89] By installing so much renewable energy, the Southwest has lowered its per capita and per dollar greenhouse gas emissions below the U.S. average.[90] Climate change can, however, decrease hydropower and fossil fuel energy generation.[91] California has enacted mandatory greenhouse gas emissions reductions,[92] and Arizona, California, Colorado, Nevada, and New Mexico have passed renewable portfolio standards to reduce fossil fuel dependence and greenhouse gas emissions.[93]

What Is New in the Fourth National Climate Assessment

This chapter builds on assessments of climate change in the Southwest region from the three previous U.S. National Climate Assessments.[94,95,96] Each assessment has consistently identified drought, water shortages, and loss of ecosystem integrity as major challenges that the Southwest confronts under climate change. This chapter further examines interconnections among water, ecosystems, the coast, food, and human health and adds new Key Messages concerning energy and Indigenous peoples.

Since the last assessment, published field research has provided even stronger detection of hydrological drought, tree death, wildfire increases, sea level rise, and warming, oxygen loss, and acidification of the ocean that have been statistically different from natural variation, with much of the attribution pointing to human-caused climate change. In addition, new research has provided published information on future vulnerabilities and risks from climate change, including floods, food insecurity, effects on the natural and cultural resources that sustain Indigenous peoples, illnesses due to the combination of heat with air pollution, harm to mental health, post-wildfire effects on ecosystems and infrastructure, and reductions of hydropower and fossil fuel electricity generation.

This chapter highlights many of the increasing number of actions that local governments and organizations have been taking in response to historical impacts of climate change and to reduce future risks (Figure 25.2). Some examples include voluntary water conservation and management in California and the Colorado River Basin, restoring cultural fire management in California, and rooftop solar policies in California, Colorado, and Nevada. Many state and local governments have issued climate change assessments and action plans.

Actions Responding to Climate Change Impacts and Vulnerabilities

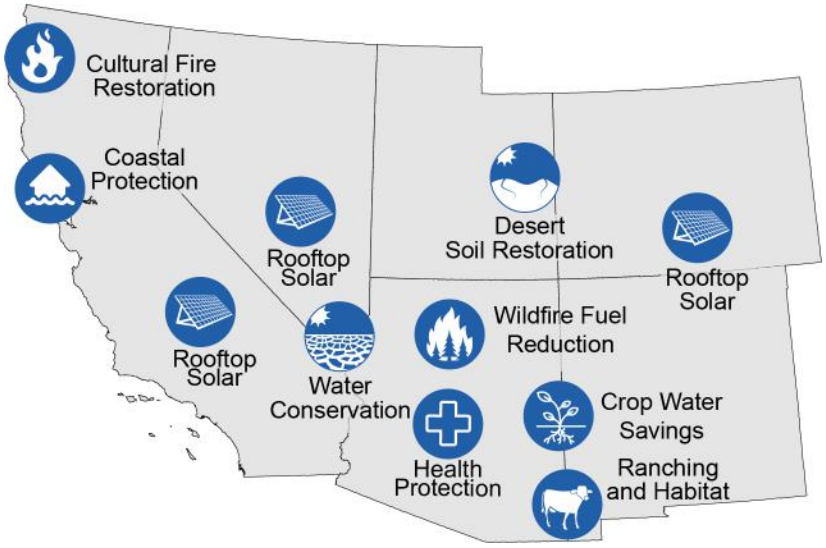


Figure 25.2: These examples illustrate actions that people, communities, and governments are taking in response to past impacts of climate change and future vulnerabilities. **Coastal protection**: In response to sea level rise and storm surge in San Francisco Bay, federal, state, and local agencies, supported by voter-approved funds, are restoring coastal habitats and levees to protect cities from flooding. **Crop water savings**: The risk of reduced food production increases as climate change intensifies drought. In the Gila River Basin, local government agencies have lined 15 miles (24 km) of irrigation canals to reduce seepage from the canals, saving enough water to irrigate approximately 8,500 acres (3,400 hectares) of alfalfa and other crops each year. **Cultural fire restoration**: Reintroduction of cultural burning by the Yurok Tribe in northern California reduces wildfire risks and protects public and tribal trust resources. **Desert soil restoration**: In Utah, transplanting native and drought-resistant microbial communities improves soil fertility and guards against erosion. **Health protection**: To reduce heat-associated injury and deaths on Arizona trails, the City of Phoenix and Arizona tourism organizations developed a campaign "Take a Hike. Do it Right." Signs at trailheads and on websites remind hikers to bring water, stay hydrated, and stay aware of environmental conditions. **Ranching and habitat**: The Malpai Borderlands Group in Arizona and New Mexico integrates native plant and wildlife conservation into private ranching. **Rooftop solar**: The state governments of California, Colorado, and Nevada have enacted policies that support rooftop solar on homes, which reduces greenhouse gas emissions, improves reliability of the electricity generation system, and creates local small businesses and new jobs. **Water conservation**: Drought in the Colorado River Basin has reduced the volume of water in both Lake Mead and Lake Powell by over half. The United States, Mexico, and state governments have mobilized users to conserve water, keeping the lake above a critical level. **Wildfire fuel reduction**: In response to severe wildfires, the City of Flagstaff, Arizona, enacted a bond to fund reduction of fire fuels in forests around the town. Source: National Park Service.

Key Message 1

Water Resources

Water for people and nature in the Southwest has declined during droughts, due in part to human-caused climate change. Intensifying droughts and occasional large floods, combined with critical water demands from a growing population, deteriorating infrastructure, and groundwater depletion suggest the need for flexible water management techniques that address changing risks over time, balancing declining supplies with greater demands.

Higher temperatures intensified the recent severe drought in California and are amplifying drought in the Colorado River Basin. In California, the higher temperatures intensified the 2011–2016 drought,[14,56,97,98,99] which had been initiated by years of low precipitation,[57,58] causing water shortages to ecosystems, cities, farms, and energy generators. In addition, above-freezing temperatures through the winter of 2014–2015 led to the lowest snowpack in California (referred to as a warm snow drought) on record.[47,55,98,100] Through increased temperature, climate change may have accounted for one-tenth to one-fifth of the reduced soil moisture from 2012 to 2014 during

the recent California drought.[14] In the ongoing Colorado River Basin drought, high temperatures due mainly to climate change have contributed to lower runoff[12,59] and to 17%–50% of the record-setting streamflow reductions between 2000 and 2014 (Figure 25.3).[13] In the Rio Grande, higher temperatures have been linked to declining runoff efficiency[60] and reductions in snowpack.[45]

Increased temperatures, especially the earlier occurrence of spring warmth,[101] have significantly altered the water cycle in the Southwest region. These changes include decreases in snowpack and its water content,[46,47,48,49,102] earlier peak of snow-fed streamflow,[103] and increases in the proportion of rain to snow.[49,103] These changes, attributed mainly to climate change,[49,103] exacerbate hydrological drought.

With continued greenhouse gas emissions, higher temperatures would cause more frequent and severe droughts in the Southwest.[11,56,62,65,80] This would also lead to drier future conditions for the region.[70,74] Higher temperatures sharply increase the risk of megadroughts—dry periods lasting 10 years or more.[61,62,65] Under the higher scenario (RCP8.5), models project annual declines of river flow in southern basins (the Rio Grande and the lower Colorado River) and either no change or modest increases in northern basins (northern California and the upper Colorado River).[78,104,105,106,107] Snowpack supplies a major portion of water in the Southwest, but with continued emissions, models project substantial reductions in snowpack, less snow and more rain, shorter snowfall seasons, earlier runoff,[55,71,78,79,108,109] and warmer late-season stream temperatures.[110] Fewer days with precipitation would lead to increased year-to-year variability.[111,112,113] Substantial increases in precipitation would be needed to overcome temperature-induced decreases in river flow.[13] The combination of reduced river flows in California and the Colorado River Basin and increasing population in southern California, which imports most of its water, would increase the probability of future water shortages.[114]

In response to the recent California drought, the state government implemented a water conservation plan in 2014 that set allocations for water utilities and major users and banned wasteful practices such as watering during or after a rainfall, hosing off sidewalks, and irrigating ornamental turf on public street medians.[115] As a result, the people of the state reduced water use 25% from 2014 to 2017, when abundant rains allowed the state to lift many restrictions while continuing to promote water conservation as a way of life.[116]

The Southern Nevada Water Authority used similar measures to reduce water use per person 38% from 2002 to 2016.[117] Water utilities in the Colorado Front Range also used similar conservation practices to reduce water use more than 20% in the early 2000s.[118] While many southwestern cities have reduced total and per-person water use since the 1990s despite growing populations,[119] ongoing drought has increased competition for reliable water supplies in many locations. In parts of Colorado, Nevada, and Utah, population growth has prompted proposals for new water diversions and transfers from agriculture. While desalination of seawater and brackish water has been proposed as a partial solution to water scarcity, its high energy requirement creates greenhouse gas emissions and its capital costs are high.[15]

Atmospheric rivers, which have caused many large floods in California,[120] may increase in severity and frequency under climate change.[82,83,107,121,122,123,124] In the winter of 2016–2017, a series of strong atmospheric rivers generated high runoff in northern California and filled reservoirs. At Oroville

Dam, high flows eroded the structurally flawed emergency spillway, caused costly damage, and led to the preventive evacuation of people living downstream. In addition to the immediate threat to human life and property, this incident revealed two water supply risks. First, summer water supplies are reduced when protective flood control releases of water from reservoirs are necessary in the spring.[108] Second, several studies have concluded that deteriorating dams, spillways, and other infrastructure require substantial maintenance and repair.[125,126] In U.S.–Mexico border cities with chronic urban storm water and pollutant runoff problems[127] and populations vulnerable to flooding,[127,128] projected increases in heavy precipitation[88] would increase risks of floods.

Wet periods present a water resource opportunity because increased infiltration from the surface into the ground recharges groundwater aquifers. Groundwater was critical for farmers during the California drought, especially for fruit and nut trees and grapevines.[129,130,131] Overdraft of groundwater, however, caused land subsidence (sinking), which can permanently reduce groundwater storage capacity and damage infrastructure as the ground deforms.[132]

In light of projected future changes in the hydrologic cycle, water resource planners and scientists are testing new techniques to combine results from multiple climate and hydrology models, downscale climate model output to finer geographic scales, calculate changing water demands, and use forecasts for flood control.[133,134,135,136] Integrating data from satellites, climate and hydrology models, and field observations remains difficult with existing water management tools, methods, and legal requirements.

Box 25.1: Collaborative Management of Colorado River Water

Since 2000, Lake Mead on the Colorado River has fallen 130 feet (40 m) and lost 60% of its volume,[137,138,139] a result of the ongoing Colorado River Basin drought and continued water withdrawals by cities and agriculture (Figure 25.3). This is the lowest level since the filling of the reservoir in 1936.[139] The reduction of Lake Mead increases the risk of water shortages across much of the Southwest and reduces energy generation at the Hoover Dam hydroelectric plant at the reservoir outlet. Local water utilities, the governments of seven U.S. states, and the federal governments of the United States and Mexico have voluntarily developed and implemented solutions to minimize the possibility of water shortages for cities, farms, and ecosystems. The parties have taken four key actions:

Hydrological drought in Lake Mead, Nevada, on March 10, 2014. Photo credit: U.S. Bureau of Reclamation.

1. Arizona, California, and Nevada agreed in 2007, with Mexico joining in 2012, to allow users to store water in Lake Mead for later years, rather than being forced to use it immediately or lose their rights.[140]

2. The United States and Mexico agreed in 2014 to release water for eight weeks to re-water the Colorado River Delta in Mexico in order to improve wildlife habitat and to conduct research on environmental restoration.[141]

Box 25.1: Collaborative Management of Colorado River Water, *continued*

3. The water agencies of Denver, Las Vegas, Los Angeles, and Phoenix and the U.S. Bureau of Reclamation in 2015 set up the Colorado River System Conservation Pilot Program, a fund for local water conservation projects. A second phase extended conservation projects to all of the Colorado River Basin.

4. Mexico agreed in 2017 to absorb a share of water shortages if Lake Mead fell below a specific elevation. The agreement continues Mexico's right to bank unused water in Lake Mead for future use. With financial and other U.S. assistance, Mexico will pursue water conservation projects and environmental restoration within the Colorado River Delta.

Currently, stakeholders are engaged in drought contingency planning for multiple climate futures, implementing management strategies that make sense for the range of climate futures, and preserving options when possible.[142]

Severe Drought Reduces Water Supplies in the Southwest

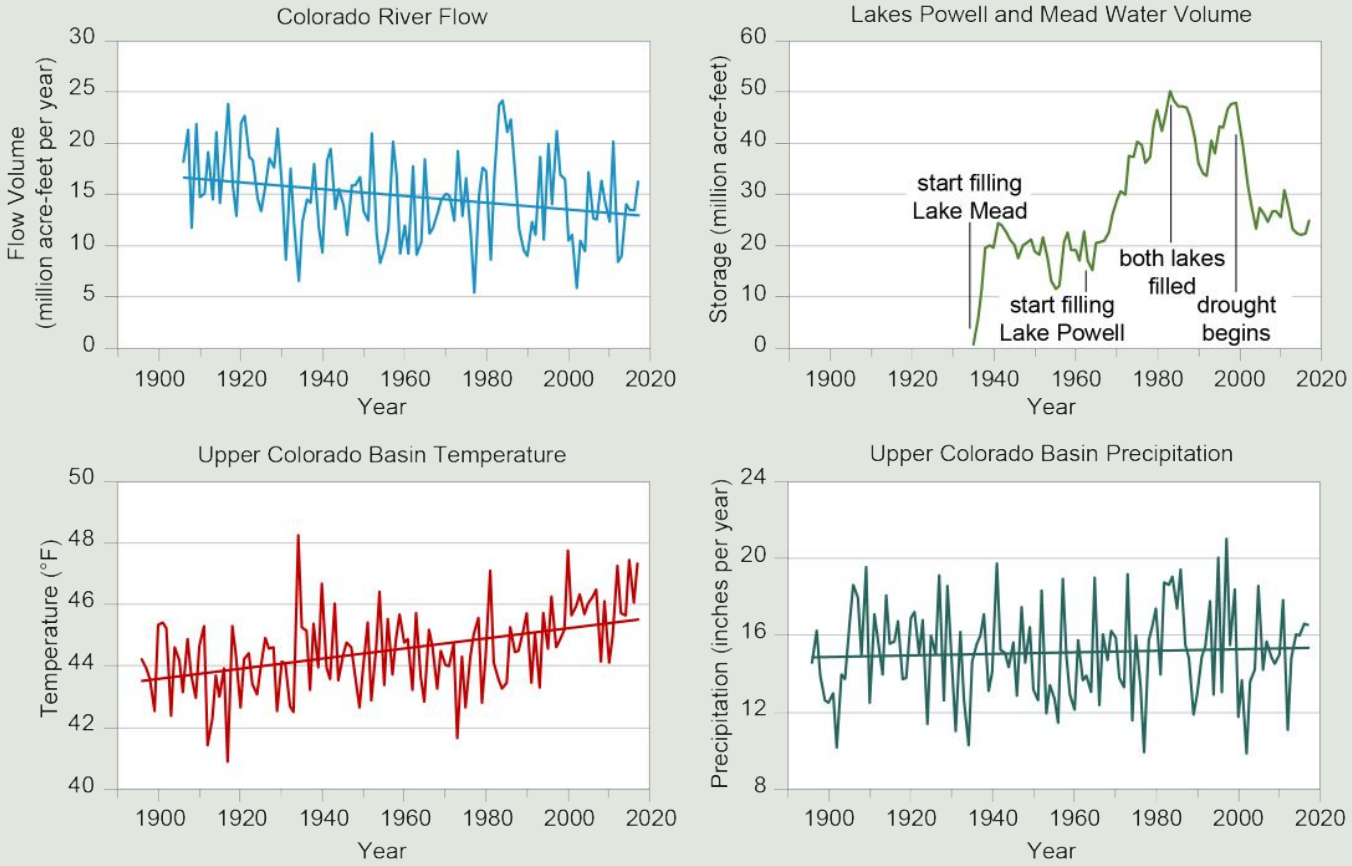


Figure 25.3: Since 2000, drought that was intensified by long-term trends of higher temperatures due to climate change has reduced the flow in the Colorado River (top left), which in turn has reduced the combined contents of Lakes Powell and Mead to the lowest level since both lakes were first filled (top right). In the Upper Colorado River Basin that feeds the reservoirs, temperatures have increased (bottom left), which increases plant water use and evaporation, reducing lake inflows and contents. Although annual precipitation (bottom right) has been variable without a long-term trend, there has been a recent decline in precipitation that exacerbates the drought. Combined with increased Lower Basin water consumption that began in the 1990s, these trends explain the recently reduced reservoir contents. Straight lines indicate trends for temperature, precipitation, and river flow. The trends for temperature and river flow are statistically significant. Sources: Colorado State University and CICS-NC. Temperature and precipitation data from: PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, accessed 20 June 2018.

Key Message 2

Ecosystems and Ecosystem Services

The integrity of Southwest forests and other ecosystems and their ability to provide natural habitat, clean water, and economic livelihoods have declined as a result of recent droughts and wildfire due in part to human-caused climate change. Greenhouse gas emissions reductions, fire management, and other actions can help reduce future vulnerabilities of ecosystems and human well-being.

The forests and other ecosystems of the Southwest region that provide natural habitat and essential resources for people have declined in fundamental ways due in part to climate change. Vast numbers of trees have died across Southwest forests and woodlands,[143,144,145,146] disproportionately affecting larger trees.[147] Tree death in mid-elevation conifer forests doubled from 1955 to 2007 due in part to climate change.[146] Field measurements showed that changes attributable, in part, to climate change, including increases in temperature, wildfire,[7] and bark beetle infestations,[148,149] outweighed non-climate factors such as fire exclusion or competition for light.[146]

Wildfire is a natural part of many ecosystems in the Southwest, facilitating germination of new seedlings and killing pests. Although many ecosystems require fire, excessive wildfire can permanently alter ecosystem integrity.[150,151] Climate change has led to an increase in the area burned by wildfire in the western United States.[7,152] Analyses estimate that the area burned by wildfire from 1984 to 2015 was twice what would have burned had climate change not occurred (Figure 25.4).[7] Furthermore, the area burned from 1916 to 2003 was more closely related to climate factors than to fire suppression, local fire management, or other non-climate factors.[152]

Climate change has driven the wildfire increase,[7,153] particularly by drying forests and making them more susceptible to burning.[154,155] Specifically, increased temperatures have intensified drought in California,[14] contributed to drought in the Colorado River Basin,[12,13]

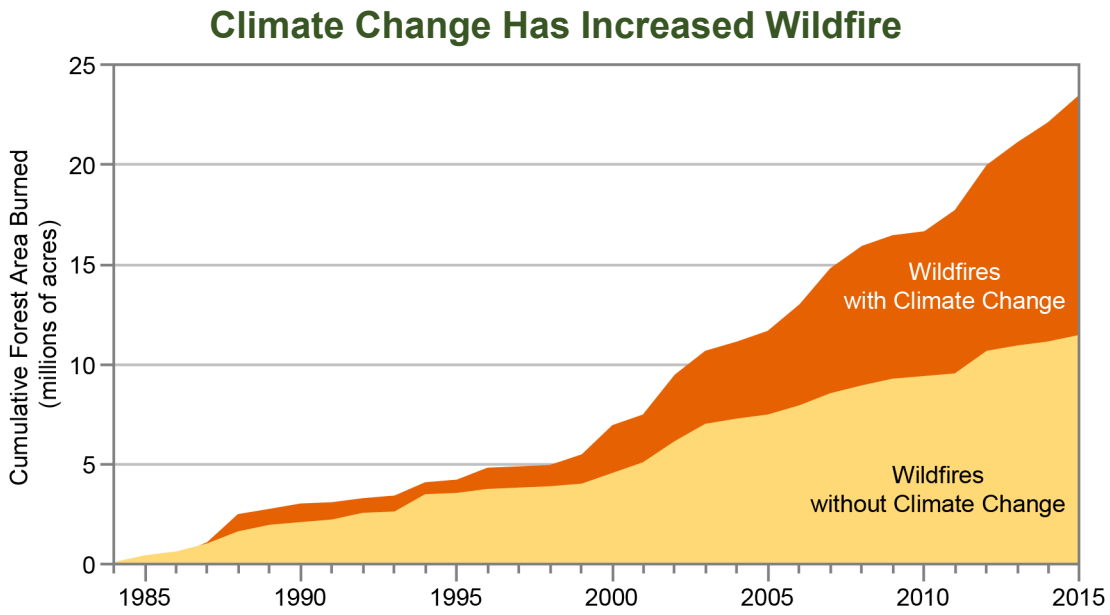


Figure 25.4: The cumulative forest area burned by wildfires has greatly increased between 1984 and 2015, with analyses estimating that the area burned by wildfire across the western United States over that period was twice what would have burned had climate change not occurred. Source: adapted from Abatzoglou and Williams 2016.[7]

reduced snowpack,[46,49,156] and caused spring-like temperatures to occur earlier in the year.[101] In addition, historical fire suppression policies have caused unnatural accumulations of understory trees and coarse woody debris in many lower-elevation forest types, fueling more intense and extensive wildfires.[150,157]

Wildfire can threaten people and homes,[159] particularly as building expands in fire-prone areas. Wildfires around Los Angeles from 1990 to 2009 caused $3.1 billion in damages (unadjusted for inflation).[159] Respiratory illnesses and life disruptions from the Station Fire north of Los Angeles in 2009 cost an estimated $84 per person per day (in 2009 dollars).[160] In addition, wildfires degraded drinking water upstream of Albuquerque with sediment, acidity, and nitrates[161,162] and in Fort Collins, Colorado, with sediment and precursors of cancer-causing trihalomethane, necessitating a multi-month switch to alternative municipal water supplies.[163,164]

Ecosystems can naturally slow climate change by storing carbon, but recent wildfires have made California ecosystems and Southwest forests net carbon emitters (they are releasing more carbon to the atmosphere than they are storing).[6,144,165] Wildfire has also exacerbated the spread of invasive plant species and damaged habitat. For example, repeated wildfire in sagebrush in Nevada and Utah has caused extensive invasions of cheatgrass, reducing habitat for the endangered sage-grouse.[64,166]

Post-wildfire erosion damages ecosystems by denuding hillsides, such as occurred in Valles Caldera National Preserve in New Mexico when the 2011 Las Conchas Fire generated the biggest local erosion event in 1,000 years.[167] In New Mexico, consecutive large wildfires degraded habitat and reduced abundance of six out of seven native coldwater fishes and some native insects, although nonnative fishes were less affected.[168]

With continued greenhouse gas emissions, models project more wildfire across the Southwest region.[169,170,171,172,173] Under higher emissions (SRES A2)[174] (see the Scenario Products section of App. 3), fire frequency could increase 25%,[172] and the frequency of very large fires (greater than 5,000 hectares) could triple.[169] The Santa Ana winds and other very dry seasonal winds increase fire risk in California[175] and Mexico.[176] Under higher emissions (SRES A2), sediment flows after fires would double in one-third of western U.S. watersheds modeled,[177] with the sediment potentially damaging ecosystems, homes, roads, and rail lines (Ch. 12: Transportation; Ch. 17: Complex Systems). Under the higher scenario (RCP8.5), cumulative firefighting costs for the Southwest could total $13 billion from 2006 to 2099 (in 2015 dollars, discounted at 3%).[178]

Reducing greenhouse gas emissions can reduce ecological vulnerabilities to wildfire.[179] For example, under a higher emissions scenario (SRES A2), climate change could triple burned area (in a 30-year period) in the Sierra Nevada by 2100, while under a lower emissions scenario (SRES B1[174]), fire would only slightly increase.[173]

Allowing naturally ignited fires to burn in wilderness and preemptively setting low-severity prescribed burns in areas of unnatural fuel accumulations can reduce the risk of high-severity fires under climate change.[180,181,182,183,184] These actions can naturally reduce or slow climate change because long-term storage of carbon in large trees can outweigh short-term emissions.[185,186] Proactive use of fire in Yosemite, Sequoia, and Kings Canyon National Parks has improved the resilience of giant sequoias and other trees to severe fires and protected their stores of carbon.[187,188,190,191]

Climate change has also contributed to increased forest pest infestations, another

major cause of tree death in Southwest forests and woodlands (Ch. 17: Complex Systems, Box 17.4). Bark beetle infestations killed 7% of western U.S. forest area from 1979 to 2012,[148,149] driven by winter warming due to climate change[103,192] and by drought.[193] Tree death from bark beetles in Colorado increased organic matter in local streams, elevating precursors of cancer-causing trihalomethane in local water treatment plants[194] to levels that exceed the maximum contaminant levels for drinking water specified by the U.S. Environmental Protection Agency.[195] Without greenhouse gas emissions reductions, further increases in heat and drought could kill many more trees,[143,196,197] especially affecting piñon pine,[198] whitebark pine,[199] and tall old-growth trees.[200] Drought hastens tree mortality over a wide range of temperatures.[201] On the Colorado Plateau in Utah, five years of hotter temperatures in experiments killed microbial biocrusts, which conserve soil fertility and protect soils from erosion.[202,203,204] In addition, grasslands[205,206] and desert plants[207,208] are vulnerable to increased plant death.

Field research in Southwest ecosystems has detected geographic shifts (Ch. 7: Ecosystems) of both plant and animal species, partly attributable to climate change. In Yosemite National Park, forest shifted into subalpine meadows from 1880 to 2002,[209] and small mammals shifted 1,600 feet (500 m) upslope from 1914 to 2006,[210] with climate change outweighing other factors as the cause.[209,210] Across the United States, including the Southwest, birds shifted northward between 0.1 and 0.5 miles (0.2 to 0.8 km) per year from 1975 to 2004, and analyses attribute the shift to climate change.[211,212]

Continued climate change would cause north–south or upslope shifts of biomes (major vegetation types) in the Southwest as vegetation follows cooler temperatures.[213] Areas highly vulnerable to such biome shifts include the Arizona Sky Islands[214] and the Sierra Nevada.[215] Potential shifts of suitable habitat for individual species include the shifting of Joshua tree habitat out of much of Joshua Tree National Park,[207,216] American pika habitat shifting off of mountain tops,[217,218] and upslope or northward shifts of numerous birds and reptiles across the Southwest.[219,220,221] Climate change may also cause shifts in the timing of plant and animal life events (phenology), including flower blooming, plant leafing, and breeding time of birds and other animals.[222,223,224] The arrival of migrating broad-tailed hummingbirds in Colorado advanced five days between 1975 and 2011.[225] Plant species that provide essential food (nectar) for the hummingbirds also shifted in phenology (Ch. 7: Ecosystems), but much more than the birds, potentially jeopardizing breeding success.

To prepare for potential future ecological changes, U.S. federal agencies have begun to integrate climate change science into resource management planning in the Southwest. For example, the U.S. National Park Service has developed park plans with specific actions for managing resources under climate change.[226] On private lands, planning that integrates native plants and wildlife into working landscapes such as farms, orchards, and ranches can promote conservation outside of protected areas and provide valued ecosystem services,

The 2013 Rim Fire in California burned more than 257,000 acres, the second largest wildfire in the Sierra Nevada and the third largest fire in California since 1932. Photo credit: Mike McMillan, U.S. Forest Service.

as demonstrated for rangelands by the Malpai Borderlands Group in Arizona and New Mexico.[227,228] In response to severe wildfires, the City of Flagstaff, Arizona, enacted a bond to provide funds to thin forest around the town perimeter.[229,230] Ecosystem restoration provides an opportunity to integrate climate change considerations into natural resource management.[231] Desert research scientists have developed the ability to grow microbial biocrusts and are testing whether translocating biocrusts that are adapted to thrive at higher temperatures can restore the soil-stabilizing, nutrient-fixing, and other services that these organisms provide in many Southwest desert ecosystems.[232,233,234] Finally, conservation of forests, especially coast redwoods, which have the highest carbon densities of any ecosystem in the world,[235] can slow or reduce climate change by naturally removing carbon from the atmosphere.[6]

Key Message 3

The Coast

Many coastal resources in the Southwest have been affected by sea level rise, ocean warming, and reduced ocean oxygen—all impacts of human-caused climate change—and ocean acidification resulting from human emissions of carbon dioxide. Homes and other coastal infrastructure, marine flora and fauna, and people who depend on coastal resources face increased risks under continued climate change.

At the Golden Gate Bridge in San Francisco, sea level rose 9 inches (22 cm) between 1854 and 2016 (Figure 25.5),[236] and in San Diego, sea level rose 9.5 inches (24 cm) from 1906 to 2016.[237] Tidal gauges around the world show increases in sea level,[238,239] and analyses show that climate change caused most of this rise by melting of land ice and thermal expansion of ocean water.[21,240,241] Non-climate-related land level changes influence relative sea level change. For example, between Cape Mendocino, California, and the Oregon border, lifting of the land at the San Andreas Fault has caused a drop in relative sea level between 1933 and 2016. Past earthquakes in the northern California coastal zone have abruptly lowered the shoreline and raised relative sea level.[242]

Under the higher scenario (RCP8.5), continued climate change could raise sea level near San Francisco by 30 inches (76 cm) by 2100, with a range of 19–41 inches (49–104 cm).[242] Currently, 200,000 people in California live in areas 3 feet (0.9 m) or less above sea level.[9] Projections of sea level rise show that this population lives in areas at risk of inundation by 2100.[9] Storm surges and high tides on top of sea level rise would exacerbate flooding.[242] In Redwood City, one-fifth of houses and one-quarter of roads are at risk of flooding under the higher scenario (RCP8.5) by 2100.[243] Sea level rise and storm surge could completely erode two-thirds of southern California beaches by 2100[244] and cause saltwater infiltration that would spoil groundwater at Stinson Beach in Marin County, California.[245] Major seaports in Long Beach and Oakland and the international airports of San Francisco, Oakland, and San Diego are vulnerable. Projected sea level rise and storm surges could cause as much as $5 billion (2015 dollars, undiscounted) in damage to property along the California coast from 2000 to 2100 under the higher scenario (RCP8.5).[178] In Point Reyes National Seashore, sea level rise threatens to inundate habitat for the endangered western snowy plover, harbor seals,[246] and northern elephant seals,[247] as well as archaeological Indigenous sites.

Governments and private landowners along the California coast have built seawalls, revetments, and other structures to protect against

sea level rise and storm surge, armoring 10% of the coastline.[248] Because hard structures often alter natural water flows and increase coastal erosion, many parties are now exploring how to restore dunes, reefs, wetlands, and other natural features to protect the coast by breaking wave energy, to increase wildlife habitat, and to preserve public access to the coast.[249]

Local governments on the California coast are using projections of sea level rise to develop plans to reduce future risks. The City of San Francisco[250] is implementing a plan that limits building in low-lying areas, constructs terraced wetlands at India Basin to facilitate upland migration of marsh habitat, and protects San Francisco International Airport with berms and seawalls along the 8-mile (13 km) shoreline. Golden Gate National Recreation Area has produced a detailed spatial analysis of the vulnerability of the marsh, paths, and buildings at Crissy Field to sea level rise and storm surges and has developed adaptation options, including moving infrastructure and establishing protective wetlands on inundated land.[251] In 2016, residents of the nine counties of the San Francisco Bay passed Measure AA, which provides funding for wetlands restoration to naturally reduce risks of flooding and inundation due to sea level rise and storm surge.

Ocean waters off the California coast and around the world warmed 0.6° to 0.8°F (0.3° to 0.5°C) from 1971 to 2010,[252] mainly due to human-caused climate change.[21] Over the past century, sea surface temperatures in the northeast Pacific Ocean (including those off the coast of California) also experienced large year-to-year and decade-to-decade variations in response to changes in wind and weather patterns that altered the exchange of heat between the ocean and atmosphere and within the upper ocean,[253] but showed overall warming from 1920 to 2016 (Figure. 25.6).

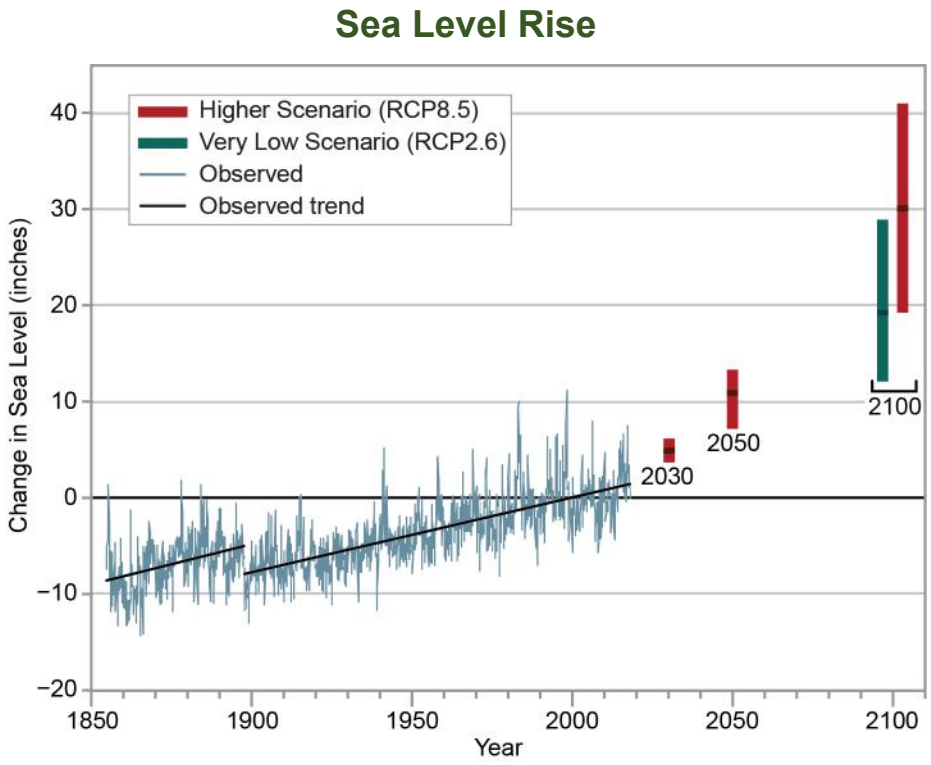


Figure 25.5: Sea level rise increases risks to infrastructure. At the Golden Gate Bridge in San Francisco, California, the tidal gauge with the longest time series in the Western Hemisphere shows that sea level has risen nearly 9 inches (22 cm) since 1854 (blue line).[236,295] In 1897, the tidal gauge was moved, which caused a slight shift downward of the numerical level but no change in the long-term trend (trends indicated by the black lines). The bars show models projections of sea levels under a higher scenario (RCP8.5; red) and a very low scenario (RCP2.6; green).[242] The change in sea level is shown relative to the 1991–2009 average. Source: National Park Service.

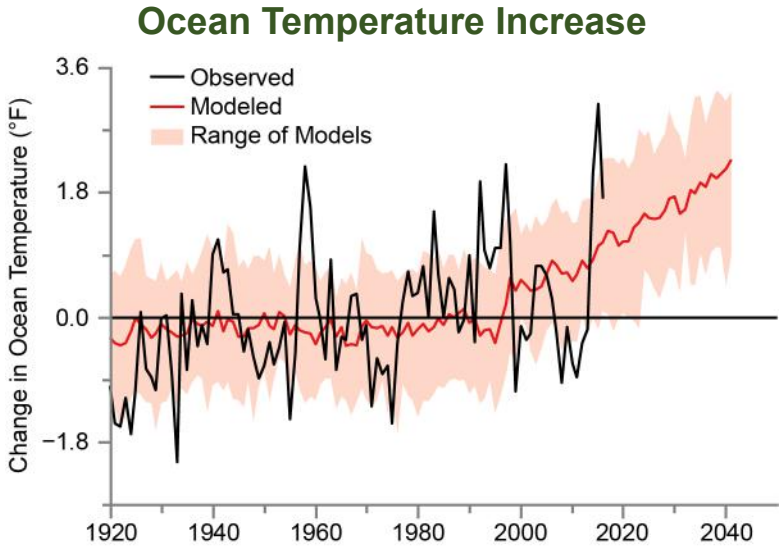


Figure 25.6 Ocean warming increases risks to fisheries and shellfish. The graph shows observed ocean temperatures of the California Current from measurements (black line); modeled temperatures, extended into the future under the higher scenario (RCP8.5; red line); and the range of 10% to 90% of the 28 models used (pink).[254,296,297] Sources: National Park Service and NOAA.

The marine heat wave along the Pacific Coast from 2014 to 2016 occurred due to a combination of natural factors and climate change.[254] The event led to the mass stranding of sick or starving birds and sea lions and shifts in pelagic (open water) red crabs and tuna into the region.[255] The ecosystem disruptions contributed to closures of commercially important fisheries and substantial reductions in California salmon catches in 2016 and 2017.[256,257,258] Ocean warming also contributed to an increase in harmful blooms of algae along the Pacific Coast.[259,260,261,262] These harmful algal blooms have produced domoic acid, which can kill people who eat tainted shellfish[261,263] and kill California sea lions.[261,264,265] Harmful algal blooms and shellfish contamination in the record warm year of 2015 delayed the commercially important Dungeness crab fishery, which contributed to a substantially reduced catch. Shifts in the timing of Dungeness and rock crab fisheries into whale migration season in 2016 contributed to increases in whale entanglements in fishing gear.[266]

Continued climate change could warm California Current waters 4°–7°F (2°–4°C) above the 1980–2005 average by 2100 (Figure 25.6).[267] This could contribute to more harmful algal blooms,[259,261] deaths of birds and sea lions, closures of fisheries, and economic loss to sectors dependent upon coastal marine resources. Under higher emissions (SRES A2), 28 fish species, including coho salmon and steelhead, could shift northward more than 180 miles (300 km) by 2050 due to higher sea surface temperatures.[268] Marine heat waves may also increase in frequency, possibly causing local disappearance of some fish and economic losses.[269]

Observed ocean water acidity off the coast of California increased 25% to 40% (decreases of about 0.10 to 0.15 pH units) from the preindustrial era (circa 1750) to the early 2000s[270,271] due to increasing emissions of carbon dioxide from human activities.[21,272] Modeling studies show that human-caused changes in ocean acidity have increased beyond what would be expected from natural variations in the early-to-mid-20th century.[273] Along the California coast, during some episodes of naturally acidic spring/summer upwelling of deeper ocean water, ocean acidity has quadrupled (a decrease of 0.7 pH units) to some of the most acidic values in the world.[274] Increased ocean acidity along California's coast has dissolved shells of some small planktonic sea snails

(pteropods), exceeding their adaptive capacity, which was developed from evolution in natural acidic upwellings.[275,276,277] In contrast, nearshore kelp forests in the northern Channel Islands off the California coast experienced few acidic events compared to local mainland sites in one three-year study.[278]

Higher carbon emissions (SRES A2) could increase the acidity of California coastal waters 40% (a decrease of 0.15 pH units) above 1995 levels by 2050.[270] In addition to damaging marine ecosystems, ocean acidification increases risks of economic losses in the shellfish industry. One ecosystem modeling study suggests negative effects of projected ocean acidification on California's state-managed crab, shrimp, mussel, clam, and oyster fisheries, but an increase in the urchin fishery.[279] Warming of ocean waters has reduced oxygen concentrations in the California Current System by 20% from 1980 to 2012.[280,281] Dissolved oxygen variations in waters far offshore affect oxygen concentrations in the California Current System nearshore.[280,282] This deoxygenation contributed to an expansion of Humboldt squid, a species that thrives in deoxygenated water, in the northeastern Pacific Ocean in the late 1990s.[283,284] Invading Humboldt squid prey on hake and other fish that are commercially important to coastal fishing communities.[283]

Climate change may reduce ocean oxygen in Pacific Ocean waters to levels lower than any naturally occurring levels as early as 2030[285] or 2050.[273] Reduced oxygen could decrease rockfish habitat off southern California by 20% to 50%.[286] Further deoxygenation may harm bottom-dwelling marine life, shrink open-water habitat for hake and other economically important species,[287] and increase the number of invasions by squid. Tracking the variability of ocean waters and fish populations and adjusting catch quotas accordingly can reduce pressures on fisheries stressed by climate change,[288] actions that have been identified as parts of the National Oceanic and Atmospheric Administration's (NOAA) Fisheries Climate Science Strategy.[289]

With continued climate change, risks would cascade from one area to another. For example, projected warmer winter temperatures in the Sierra Nevada would increase winter runoff, reduce spring and summer freshwater inflows into San Francisco Bay, and increase salinity in the Bay 3 to 5 grams per kilogram of water by 2100.[290,291,292] Also, sea level rise and storm surge would compound effects inland of river and stream flooding, putting houses and roads at risk of inundation and damage.[293,294]

Key Message 4

Indigenous Peoples

Traditional foods, natural resource-based livelihoods, cultural resources, and spiritual well-being of Indigenous peoples in the Southwest are increasingly affected by drought, wildfire, and changing ocean conditions. Because future changes would further disrupt the ecosystems on which Indigenous peoples depend, tribes are implementing adaptation measures and emissions reduction actions.

Droughts in the Southwest have contributed to declines in traditional Indigenous staple foods, including acorns, corn, and pine nuts.[298,299,300] Drought and increasing heat intensify the arid conditions of reservations where the United States restricted some tribal nations in the Southwest region to the driest portions of their traditional homelands.[301] Navajo elders tell of the increasingly arid conditions over the last half of the 20th century that contributed to declines in culturally significant crops, the flow of specific water springs and seeps, and wildlife populations, such as eagles.[44,302] Projected

reductions in water supply reliability,[13,114] coupled with water agreements that involve selling or leasing tribal water to neighboring communities, could place tribal water supplies at risk during severe shortages. As water supplies decrease and water demand increases, tribes are at risk of finding themselves committed to providing purchased water to other entities, resulting in situations in which, in the words of one elder, "water sold must be delivered, regardless of the condition of the selling reservation. In this worst-case scenario, the Community will have to breach its contracts for the survival of its people."[303]

In addition to drought, wildfires affect traditional resources, including fish, wildlife, and plants, such as tanoaks and beargrass, upon which some Southwest tribes rely for food and cultural uses.[304,305,306] Continued climate change would reduce populations of some fish, wildlife, and plants that serve as traditional foods, medicines, and livelihood and cultural resources.[298,307,308] Reduced availability of traditional foods often contributes to poorer nutrition and an increase in diabetes and heart disease.[298,309] Reductions in runoff would, for example, increase the salinity of Pyramid Lake in Nevada, reducing fish biodiversity and affecting the cui-ui fish, the primary cultural resource of the Pyramid Lake Paiute Tribe.[310] Tribes in the Southwest that depend on livestock are at risk of climate-related degradation of rangelands.[44,311,312] Many California tribes, including the Miwok, Paiute, Western Mono, and Yurok, among others, are concerned about the loss of acorns—a nutritious traditional food, medicine, and basketry component[313,314]—due to sudden oak death, which can increase with changes in humidity and temperature.[44,312,315] Changes in plant and animal ranges (Ch. 7: Ecosystems, KM 1) can also affect mental and spiritual health, disrupting cultural connections to disappearing plant and animal relatives and to place-based identity and practices.[42,316]

Changes in marine ecosystems affect resources for Indigenous peoples (Ch. 15: Tribes). Ocean warming affects salmon and other fish on which Pacific Coast tribes rely for subsistence, livelihoods, and cultural identity.[307,317,318,319,320] Ocean warming and acidification, as well as sea level rise, increase risks to shellfish beds (which reduces access for traditional harvesting),[298] pathogens that cause shellfish poisoning,[307,311] and damage to shellfish populations, which can cause cascading effects in food and ecological systems upon which some tribes depend.[298,321]

Although Indigenous peoples have adapted to climate variations in the past, historical intergenerational trauma, extractive infrastructure, and socioeconomic and political pressures[322,323] reduce their adaptive capacity to current and future climate change (Ch 15: Tribes, KM 1 and 3).[324] Still, in response to climate change, Indigenous peoples in the Southwest are developing new adaptation and mitigation actions based on a cultural model focused on relationships between humans and nonhumans.[313,325,326] Traditional ecological knowledge of specific plants and habitats can enable Indigenous peoples to provide early detection of invasive species and support to ecological restoration.[327] Some tribes, such as the Tesuque Pueblo of New Mexico, use their knowledge to reintegrate traditional foods into their diets. Other tribes, such as the Karuk Tribe,[304] North Fork Mono,[313] and Mountain Maidu[328] use traditional ecological knowledge to guide natural resource management. The Yurok Tribe, Gila River Indian Community, and Tohono O'odham Nation, among others, are developing climate adaptation plans, often in partnership with universities and other research institutions (Ch. 15: Tribes, KM 3 and Figure 15.1).

Many Indigenous peoples in the Southwest region have traditionally used fire as a tool central to cultural and spiritual practices. They use fire to protect and enhance species used for basket weaving, medicines, and traditional

foods.[306,313,328,329,330,331,332] This cultural use of fire offers an important tool for adaptation and mitigation, as traditional burning reduces fuel accumulations that can lead to high-severity wildfires (see Case Study "Cultural Fire and Climate Resilience" and Figure 25.7).[331,333]

Case Study: Cultural Fire and Climate Resilience

Indigenous peoples in the Southwest have traditionally used fire as a tool central to social, cultural, and spiritual practices. They use fire to increase ecosystem resilience, reduce fuel loads, manage crops, and protect species used for basket weaving, medicines, and traditional foods.[306,313,328,329,330,331,332] Tribal entities are restoring cultural burning practices and management principles that guide the use of fire on the landscape to reduce wildfire risks and protect public and tribal trust resources.[331,333] For example, Yurok tribal members have formed the Cultural Fire Management Council (CFMC), in partnership with the Nature Conservancy Fire Learning Network, Firestorm Inc., Yurok Forestry/Wildland Fire, Northern California Indian Development Council, and the U.S. Department of Agriculture (USDA) Forest Service, to bring fire back to the landscape for ecosystem restoration.[334] The collaboration builds capacity and trains Yurok and local fire crews through the Prescribed Fire Training Exchange. "Restoration of the land means restoration of the people," said CFMC President Margo Robbins, "Returning fire to the land enables us to continue the traditions of our ancestors."[334]

Cultural Fire on Yurok Reservation

Figure 25.7: Andy Lamebear, a Yurok Wildland Fire Department firefighter and Yurok tribal member, ignites a cultural burn on the Yurok Reservation. The tribe uses low- to medium- intensity fires to enhance the production of plant-based medicines, traditional basket materials, native fruits, and forage for wildlife. Cultural burning also reduces risks of catastrophic wildfire. Photo courtesy of the Yurok Tribe.

Key Message 5

Energy

The ability of hydropower and fossil fuel electricity generation to meet growing energy use in the Southwest is decreasing as a result of drought and rising temperatures. Many renewable energy sources offer increased electricity reliability, lower water intensity of energy generation, reduced greenhouse gas emissions, and new economic opportunities.

Hydroelectric generation depends on sufficient water supplies. The severe drought in California, intensified by climate change,[14,56] reduced hydroelectric generation by two-thirds from 2011 to 2015.[335] Drought in the Colorado River Basin[13,59] caused river runoff, on which hydroelectric generation depends,[12,336,337] to decline. By 2016, Lake Mead, which stores water for drinking, agriculture, and the Hoover Dam hydroelectric plant, had fallen by half (Box 25.1 and Figure 25.3). Although the Bureau of Reclamation maintained constant electricity generation at Hoover Dam throughout the drought, this decline potentially reduces maximum generation capacity.

In California, utilities increased fossil fuel generation of electricity to compensate for the drought-driven decline in hydroelectricity, increasing state carbon dioxide emissions in the first year of the drought (2011 to 2012) by 1.8 million tons of carbon, the equivalent of emissions from roughly 1 million cars.[338,339] A drop in the price of natural gas also contributed to the increase, although the shift from hydroelectric to fossil fuels cost California an estimated $2.0 billion (in 2015 dollars).[340] Other southwestern states also shifted some generation from hydropower to fossil fuels.[89]

Under a higher scenario (RCP8.5), declines in snowpack and runoff in the Colorado River and Rio Grande Basins and a shift of spring runoff to earlier in the year[105] would reduce hydroelectric power potential in the region by up to 15% by 2050.[91] Under a very low scenario (RCP2.6), hydroelectric generation may remain unchanged, demonstrating the positive benefits of emissions reductions.[91] With increased precipitation, hydroelectric potential could increase,[342] except in cases of reservoir spillage to protect dams in extreme storms.[343]

The efficiency of water-cooled electric power plants that burn fuel depends on the temperature of the external cooling water, so climate change could reduce energy efficiency up to 15% across the Southwest region by 2050.[91] Since higher temperatures also increase electric resistance in transmission lines, electricity losses in many transmission lines across the Southwest could reach 5% by 2080 under a lower scenario (RCP4.5) and 7% under a higher scenario (RCP8.5).[344] Under the higher scenario (RCP8.5), water demand by thermoelectric plants in the Southwest is projected to increase 8% by 2100.[345] In a 10-year drought, summer electric generating potential in the Southwest could fall 3% to 9% under higher emissions (SRES A2) or 1% to 7% under lower emissions (SRES B1; Figure 25.8).[346]

Any increase in water requirements for energy generation from fossil fuels would coincide with reduced water supply reliability from projected decreases in snowpack[46,77] and earlier snowmelt.[75,347] Increased agricultural water demands under higher temperatures could affect the seasonal demand for hydropower electricity.[105] The water consumption, pollution, and greenhouse gas emissions of hydraulic fracturing (fracking) make that source of fuel even less adaptive under climate change.[348] Substantial energy and carbon emissions are embedded in the pumping, treatment, and

transport of water, so renewable-powered water systems are less energy and carbon intense than ones powered by fossil fuels.[349]

Economic conditions and technological innovations have lowered renewable energy costs and increased renewable energy generation in the Southwest. For example, wind energy generation in California rose by half from 2011 to 2015, and solar energy generation increased by 15 times.[335]

Solar, wind, and other renewable energy sources, except biofuels, emit less carbon and require less water than fossil fuel energy. By cutting carbon emissions, renewable energy can reduce future impacts of climate change on nature and human well-being.[30,350,351,352] After the first year of the drought, when natural gas burning increased to compensate for a loss of hydroelectric energy, solar and wind energy sources in California increased enough to displace 15% of fossil fuel burning for electricity from 2012 to 2017, thereby reducing state greenhouse gas emissions by 6%.[335] Increased electricity generation by renewable sources can cut water needs up to 90% in the Southwest, depending on the fraction of production derived from fossil fuels.[353,354] Under a higher scenario (RCP8.5), conversion of two-thirds of fossil fuel plants to renewables would reduce water demand by half.[345]

State energy policies are facilitating the switch to renewable energy. Arizona, California, Colorado, Nevada, and New Mexico have enacted renewable energy portfolio standards.[93] California has set the highest standard: 50% of energy generation from renewable sources by 2030. In 2017, renewable energy sources supplied 32% of California energy generation.[355] By 2013, these standards had averted 26 trillion watt-hours of fossil fuel generation in the Southwest and 3% of carbon emissions nationally and had produced $5 billion in health benefits from reduced air pollution (in 2013 dollars; $5.2 billion in 2015 dollars).[356] Potential future benefits of existing renewable portfolio standards include carbon emission reductions of 6% nationally and health benefits of $560 billion (in 2013 dollars; $577 billion in 2015 dollars) from 2015 to 2050.[357]

Electricity Generation Capacity at Risk Under Continued Climate Change

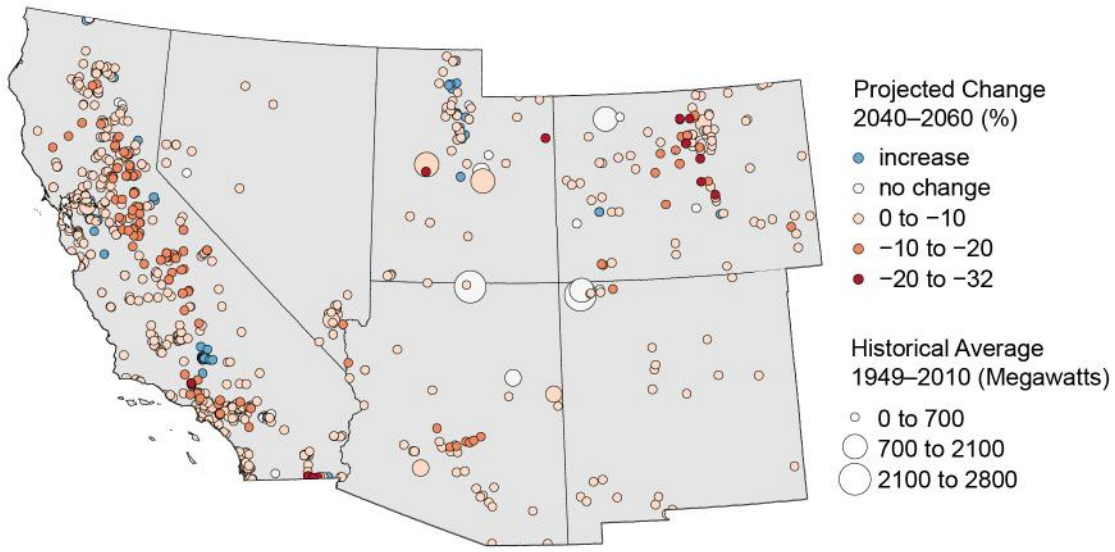


Figure 25.8: Under a higher emissions scenario (SRES A2[174]), heat-induced reduction of energy efficiency and reduced water flows would reduce summer energy generation capacity across the Southwest region. These projected reductions would increase risks of electricity shortages. The map shows projected changes for the period 2040–2060 compared to the period 1949–2010. Source: adapted from Bartos and Chester 2015.[346] Reprinted by permission from Macmillan Publishers Ltd.

Distributed solar energy systems place individual solar panels on roofs, on parking lot canopies, and other built places. The high number of sunny days in the Southwest and the great extent of existing rooftops and parking lots create a high potential for distributed solar generation, which could provide two-thirds of electricity use in California.[358] Distributed solar uses land that has already been urbanized and is close to energy users, reducing the need for transmission lines and transmission line electricity losses. Compared to industrial centralized solar power systems, distributed solar causes less death and disruption to wildlife that are already vulnerable to climate change, such as birds and endangered desert tortoises.[359] California, Colorado, and Nevada have enacted policies that support rooftop solar on homes, in particular net metering, in which customers sell their excess solar electricity to the grid.[360] Distributed wind energy systems can provide similar benefits.

Arizona, California, Colorado, Nevada, and New Mexico have enacted energy efficiency standards for utilities. California and New Mexico have also enacted policies that decouple utility profits from electricity sales.[361] White or reflective roofs, known as cool roofs, increase energy efficiency of buildings. Under a higher scenario (RCP8.5), cool roofs would reduce urban heat islands in Los Angeles and San Diego 2°–4°F (1°–2°C) by 2050 and decrease energy use and the use of air conditioning.[362] Urban tree planting in Phoenix that would increase tree cover from 10% to 25% would provide daytime cooling of up to 2°C in local neighborhoods.[363]

Newer technologies now allow generating plants to use nontraditional water sources, including saline groundwater, recycled water from landscaping, and municipal and industrial wastewater. For example, the Palo Verde Nuclear Generating Station in Arizona uses municipal wastewater.[361] Other plants in the region use extremely water-efficient hybrid wet–dry cooling technology. For instance, the Afton Generating Station in New Mexico is a natural gas combined-cycle plant that uses hybrid cooling to reduce water intensity by 60% compared to conventionally cooled plants.[361]

Electric cars can reduce fossil fuel use and greenhouse gas emissions compared to gasoline-powered vehicles. The relative greenhouse gas emissions from electric and gasoline vehicles depend on how the electricity is generated.[364,365] If the electricity is produced from renewable sources, then the operating emissions for electric vehicles are near zero, although the manufacturing of the vehicle emitted greenhouse gases. Conversely, if the electricity is produced completely from fossil fuel, the emissions from the electric vehicle are higher because of the limit of energy efficiency of large power plants and transmission line losses. Because sunlight, wind, and other renewable resources are intermittent and sometimes not available at times of demand, charging at night and improvements in battery technology would facilitate renewable energy generation.

Key Message 6

Food

Food production in the Southwest is vulnerable to water shortages. Increased drought, heat waves, and reduction of winter chill hours can harm crops and livestock; exacerbate competition for water among agriculture, energy generation, and municipal uses; and increase future food insecurity.

Climate change has altered factors fundamental to food production and rural livelihoods in the Southwest, particularly the shortage of water caused by droughts in California[14,56] and the Colorado River Basin.[13] The California drought led to losses of more than 10,000 jobs and the fallowing of 540,000 acres (220,000 hectares), at a cost of $900 million in gross crop revenue in 2015.[130] Increased temperatures in the Southwest also affected agricultural productivity from 1981 to 2010.[366]

Food production depends on reliable surface and groundwater supplies, which decline from droughts and reductions in snowpack and soil moisture.[67] Irrigated agriculture and livestock water use accounted for approximately three-quarters of total water use in the Southwest in 2010, excluding Colorado, which has wide-ranging dryland wheat production.[16,367,368] In the recent California drought, domestic wells dried out in some rural communities, but increased groundwater pumping from deeper wells prevented some agricultural revenue losses.[369] Falling groundwater tables increase pumping costs and require drilling to deepen wells.[130] Drought-related agricultural changes, stricter drilling regulations, and rapid aquifer depletion have already led to a decline in irrigation in parts of the region. According to climate projections for lower and higher emissions scenarios (RCP4.5 and RCP8.5), future changes in climate would reduce aquifer recharge in the southern part of the region by 10%–20%,[370] removing some of the secondary water source responsible for buffering effects of severe drought. In the Gila River Basin of New Mexico, farmers shift to groundwater pumping when surface water supplies are reduced, despite associated increases in production costs.[371] Under continued climate change, increased drought risk[13] and higher aridity[70] could expose some agricultural operations in the Southwest to less reliable surface and groundwater supplies (Ch. 10: Ag & Rural, KM 1).

Under continued climate change, higher temperatures would shift plant hardiness zones northward and upslope (Figure 25.9). These changes would affect individual crops differently depending on optimal crop temperature thresholds. Some crops, including corn[372] and rice,[373] are already near optimal thresholds in the Southwest. Increasing heat stress during specific phases of the plant life cycle can increase crop failures, with elevated temperatures associated with failure of warm-season vegetable crops and reduced yields or quality in other crops.[374] While crops grown in some areas might not be viable under hotter conditions, crops such as olives, cotton, kiwi, and oranges may replace them.[375] In parts of the Southwest region, increasing temperatures would prompt geographic shifts in crop production, potentially displacing existing growers and affecting rural communities.[376] Wine grape quality can be particularly influenced by elevated temperatures.[377] Increased levels of ozone and carbon dioxide near the surface, combined with increases in temperature, can decrease food quality and nutritive values of fruit and vegetable crops.[378,379]

Because many fruit and nut trees require a certain period of cold temperatures in the winter, decreased winter chill hours under continued climate change would reduce crop yields, though the magnitude may vary considerably.[380] In Yolo County, California, reduced winter chill may make conditions too hot for walnut cultivation by 2100.[381] California almond acreage has nearly doubled over the last two decades due to high foreign demand and the favorable Mediterranean climate. California now produces over 80% of world almond supply.[382] Since almonds also have a relatively high water requirement, both water and adequate cool winter temperatures will be important factors to maintain California tree nut production under climate change.

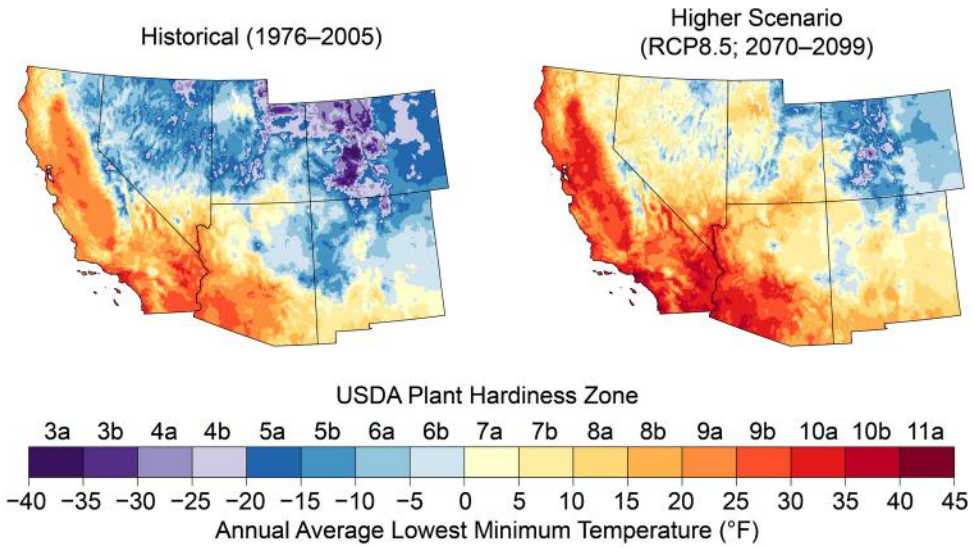


Figure 25.9: The U.S. Department of Agriculture plant hardiness zones indicate the cold temperature requirements of crops. Increases in temperature under the higher scenario (RCP8.5), would shift these zones northward and upslope, from the period 1976—2005 (left, modeled historical) compared to projections for 2070—2099 (right, average of 32 general circulation models). Sources: NOAA NCEI and CICS-NC.

Climate-related vulnerabilities of the Southwest region's livestock industry include reduced long-term livestock grazing capacity, reduced feed supply, increased heat stress (Ch. 10: Ag & Rural, KM 3), and reduced forage quality.[383] Water-intensive forage crops are especially vulnerable to water shortages.[15] Although livestock production systems persist in highly variable conditions, projected high temperatures may decrease production of rangeland vegetation and livestock forage.[384] In response to drought (1999–2004), 75% of Utah ranch operations reported major reductions in water supply, forage, and cattle productivity.[385] Only 14% felt they were adequately prepared for the drought, which may be reflected in the high use of federal relief programs.

One potential adaptation of agriculture to drought is water banking, the storage of excess surface water in groundwater aquifers.[386,387] For example, streamflows from the Sierra Nevada in high-precipitation years could provide substantial groundwater recharge in the California Central Valley.[388] Additional options include expanding surface reservoir storage or relying upon groundwater pumping, although this further depletes limited groundwater stores.[389]

Flexible livestock management strategies, such as stocking rates, grazing management practices, employing livestock bred for arid environments, erosion control, and identification of alternate forage supplies can help reduce vulnerability in an increasingly arid and variable climate.[390,391] Criollo cattle appear well-suited for the arid Southwest because they are more heat tolerant and adaptive than traditional breeds.[392]

In urban areas across the Southwest, such as Tucson, Arizona, and Sacramento, California, community food banks that grow food in community gardens can help maintain food security in a drier and more variable climate. Urban gardens and local food organizations provide fresh produce, foster community education, and support networks of local growers. These organizations build food systems capacity, which helps to mitigate impacts of urban heat, reduces food transportation costs and

emissions, and supports provision of fresh local food to low-income urban dwellers.

Additional emerging issues that increase risks to food production include invasive nonnative or alien insect pests (introduced into the region intentionally or unintentionally) that are more adapted to hotter temperatures.[393] Global trade and efficient transportation also increase risks of invasion by alien insect pests. A mismatch in timing between plant flowering and the arrival of insect pollinators would reduce crop production and pollinator survival.[393] In addition, some subsistence foods, such as fish, upon which some Indigenous and other subsistence and urban communities depend,[309,394,395,396,397] and spiritually, socially, and culturally important tribal traditional foods[298] would be vulnerable in a drier and more variable climate (Key Message 4).

Key Message 7

Human Health

Heat-associated deaths and illnesses, vulnerabilities to chronic disease, and other health risks to people in the Southwest result from increases in extreme heat, poor air quality, and conditions that foster pathogen growth and spread. Improving public health systems, community infrastructure, and personal health can reduce serious health risks under future climate change.

Exposure to hotter temperatures and heat waves has led to heat-associated deaths and illnesses in Arizona and California.[398,399,400,401,402,403] In the unprecedented 2006 California heat wave, which affected much of the state and part of Nevada, extremely high temperatures occurred day and night for more than two weeks.[404] Compared to non-heat wave summer days, it is estimated that the event led to an additional 600 deaths, 16,000 emergency room visits, 1,100 hospitalizations in California,[399,405,406] and economic costs of $5.4 billion (in 2008 dollars).[405] Parts of the Southwest region experienced record-breaking heat in five of the six years from 2012 to 2017.[25,26,27,28,29] Assessments of the health impacts associated with record high temperatures in parts of the Southwest since 2010 are not yet available in the scientific literature.

Under continued climate change, projected increases in hot days and extreme heat events in the Southwest (Figure 25.10)[23,24,404,407] will increase the risk of heat-associated deaths.[30] Under the higher scenario (RCP8.5), the Southwest would experience the highest increase in annual premature deaths due to extreme heat in the country, with an estimated 850 additional deaths per year and an economic loss of $11 billion (in 2015 dollars) by 2050.[178] Under a lower scenario (RCP4.5), deaths and costs would be reduced by half compared to the higher scenario (RCP8.5).[178] By 2090, deaths and economic losses would more than double from 2050 under all emissions scenarios.[178] Heat and other environmental exposures particularly affect outdoor workers.[178] Under the higher scenario (RCP8.5), extreme heat in the Southwest (Figure 25.10) would also lead to high labor losses, including losses of high-risk labor hours of up to 6.5% for some counties by 2090 and of $23 billion per year in regionwide wages (in 2015 dollars).[178] It is projected that the lower scenario (RCP4.5) would reduce those wage losses by half.[178]

The risk of illness or death associated with extreme temperatures can be reduced through targeted public health and clinical interventions.[30,32] The main factors that put individuals and populations at increased risk in a heat wave are age (children and older adults are most at risk), hydration status, and presence of a chronic disease such as obesity, cardiovascular or respiratory disease, or psychiatric illness.[400,408,409,410,411,412,413,414,415] Psychosocial stresses and socioeconomic conditions, such as hot and poorly ventilated homes or lack of access to public emergency cooling centers can elevate these risks.[31,33,416]

Without adoption and implementation of strategies to minimize exposures to extended periods of extreme heat, the public health impacts of future heat waves may be as serious as those observed in California in 2006. The technological and behavioral adaptations to heat developed by populations in the Southwest are based on the observed historical range of nighttime minimum temperatures.[404] Projected increases in minimum temperatures and decreases in the number of cool nights[23] may diminish the efficacy of these adaptations.

Climate change and variability can also increase communicable and chronic disease burdens.[417,418,419] While infectious diseases like plague and hantavirus pulmonary syndrome disproportionately affect the Southwest region,[158] new research to support estimating future climate-associated risk for these diseases is sparse.[420] Therefore, this assessment focuses on recent developments in the understanding of heat, air quality, mosquito-borne diseases, and Valley fever and vulnerabilities that influence them.

In addition to extreme heat, the environmental conditions of greatest concern for human health are ground-level ozone air pollution, dust storms, particulate air pollution (such as from wildfires and dust storms), aeroallergens (airborne substances that trigger allergic reactions), and low water quality and availability.[30,178] In addition, alternating episodes of drought and extreme precipitation coupled with increasing temperatures promote the growth and transmission of pathogens.[30,421] The risk of onset or exacerbation of respiratory and cardiovascular disease is associated with a single or a combined exposure to ground-level ozone pollution, particulate air pollution, respiratory allergens, and extreme heat. Ground-level ozone is produced by chemical reactions of combustion-related chemicals (for example, from vehicles or wildfires) in a reaction that is dependent on ultraviolet radiation (that is, from the sun) and amplified by higher temperatures. Once formed, ozone can travel great distances and persist in high concentrations overnight in rural areas. Among many health impacts, ozone can promote or aggravate asthma and respiratory allergies.[422,423,424,425]

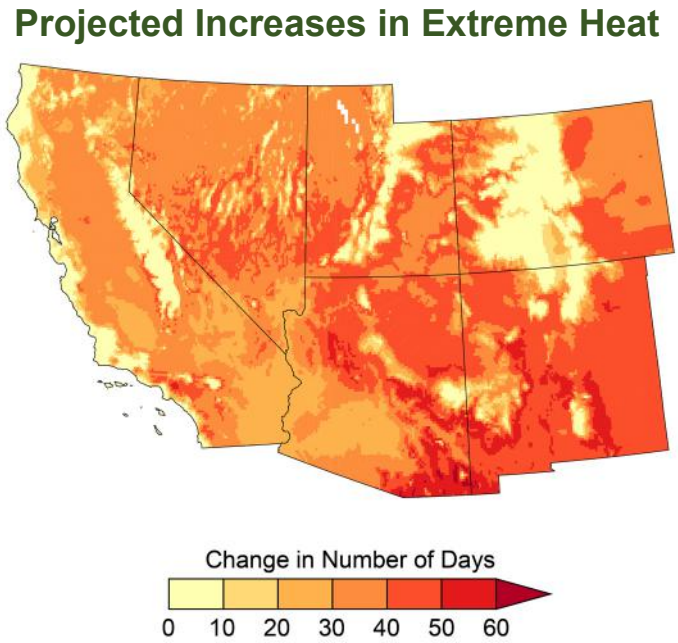


Figure 25.10: Under the higher scenario (RCP8.5), extreme heat would increase across the Southwest, shown here as the increase in the average number of days per year when the temperature exceeds 90°F (32°C) by the period 2036–2065, compared to the period 1976–2005.[23] Heat waves increase the exposure of people to heat stroke and other illnesses that could cause death.[30] Source: adapted from Vose et al. 2017.[23]

Elevated levels of CO_2 in conjunction with higher temperatures can increase the amount and potency of aeroallergens (Ch. 14: Human Health, KM 1). These conditions may also lead to new cases or exacerbation of allergy and asthma.[426,427,428,429] Mortality risk during a heat wave is amplified on days with high levels of ground-level ozone or particulate air pollution, with the greatest mortality due to cardiovascular causes.[430]

Severe dust storms in the Southwest contribute to respiratory and cardiovascular disease.[431,432] The association between Valley fever, a soilborne fungal respiratory infection of the Southwest, and warmer temperatures and soil dryness varies across the region and by time of year.[189,433,434] The connection between climate change, dust storm frequency and severity, and future public health effects in the region is complex and remains an emerging area of research.[435,436,437,438,439] Heat extremes, warming, and changes in precipitation will also influence the distribution and occurrence of vector-borne diseases like West Nile virus[440,441,442,443] and may lead to the emergence of new disease (Ch. 14: Human Health, KM 1).[30] Without proactive interventions and policies that address the biological, exposure, and socioeconomic factors that influence individual and population vulnerability, adverse health impacts may increase (Ch. 14: Human Health, KM 2). Those increases may disproportionately affect people with the lowest incomes, which hinders adaptive capacity (Ch. 14: Human Health, KM 1).[416,444]

Climate-related hazards such as heat waves, flooding, wildfires, or large disease outbreaks require emergency responses. Prolonged droughts can affect drinking water availability, reduce water quality,[445] and send more people seeking medical treatment.[446,447] The increased burden of disease can outpace the resources and adaptive capacity of public health and clinical infrastructures. The region may not be prepared to absorb the additional patient load that could accompany climate change,[448] but integrating risk reduction strategies into emergency response plans and recognizing and addressing vulnerability factors can appreciably reduce risks of future adverse health consequences (Ch. 14: Human Health, KM 3). This approach is embodied in the Centers for Disease Control and Prevention's (CDC) Building Resilience Against Climate Effects framework for adaptation planning.[449] Adaptation planning is already yielding health protection benefits.[450]

Local government agencies are preparing for extreme events by developing and updating emergency response plans and improving public warning and response systems. In 2014, California updated its Contingency Plan for Excessive Heat Emergencies,[451] Arizona released its Heat Emergency Response Plan,[452] and Salt Lake City, San Francisco, and Sonoma County were recognized in the first cohort of U.S. Department of Energy Climate Action Champions. Integrated and participatory planning for extreme heat,[453] such as the Capital Region Climate Readiness Collaborative in Sacramento, California, can help overcome institutional and governance barriers to implementing adaptation actions (Ch. 28: Adaptation).[454]

Policies and interventions related to one health factor can positively affect other factors and yield co-benefits[455,456,457,458,459] For example, research shows that heat-associated deaths and illnesses are preventable[460] and that healthier individuals are less susceptible to adverse effects of extreme heat exposure. Obesity, which affects about 30% of adults and 15% of school-age children and teens nationwide, increases the risk for many chronic diseases, such as asthma and diabetes, and increases the risk for serious heat-related adverse health outcomes.[32,461,462,463] Access to healthcare, social

isolation, housing quality, and neighborhood poverty are also key risk factors for heat-related health impacts.[31,33,412]

Urban design strategies to address these risk factors include increasing walkability and bicycle safety and maintaining and planting trees and green space.[464] These strategies can achieve multiple health benefits, including increasing physical activity, thereby helping residents maintain a healthy weight,[465,466] reducing the urban heat island effect,[467] and reducing exposure to harmful air pollutants from vehicles. Reducing the urban heat island effect also reduces energy demand and risks of power outages, which can contribute to health risks, such as patients losing access to electricity-dependent medical devices.

Climate change may weigh heavily on mental health in the general population and those already struggling with mental health disorders.[468,469,470,471,472] One impact of rising temperatures, especially in combination with environmental and socioeconomic stresses, is violence towards others and towards self.[473,474,475] Slow-moving disasters, such as drought, may affect mental health over many years.[470] Studies of chronic stress indicate a potentially diminished ability to cope with subsequent exposures to stress.[476,477,478]

Populations under chronic social and economic stresses in urban and rural areas possess lower psychological, physical, and economic resilience (Ch. 10: Ag & Rural, KM 3). Communities that rely especially on well-functioning natural and agricultural systems in specific locations may be especially vulnerable to mental health effects when those systems fail. In the Southwest, the loss of stability and certainty in natural systems may affect physical, mental, and spiritual health of Indigenous peoples with close ties to the land.[42,316] For example, extended drought raises concerns about maintaining Navajo Nation water-based ceremonies essential for spiritual health, livelihoods, cultural values, and overall well-being.[301]

Acknowledgments

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Traceable Accounts

Process Description

The authors examined the scientific literature in their areas of expertise. The team placed the highest weight on scientific articles published in refereed peer-reviewed journals. Other sources included published books, government technical reports, and, for data, government websites. The U.S. Global Change Research Program issued a public call for technical input and provided the authors with the submissions. The University of Arizona Center for Climate Adaptation Science and Solutions organized the Southwest Regional Stakeholder Engagement Workshop on January 28, 2017, with over 70 participants at the main location in Tucson, AZ, and dozens of participants in Albuquerque, NM, Boulder, CO, Davis, CA, Los Angeles, CA, Reno, NV, and Salt Lake City, UT, all connected by video. Participants included scientists and managers. The author team met the following day for their only meeting in person. Subsequently, authors held discussions in regular teleconferences. Many chapter authors met at the all-author meeting March 26–28, 2018, in Bethesda, MD.

Key Message 1

Water Resources

Water for people and nature in the Southwest has declined during droughts, due in part to human-caused climate change (*very high confidence*). Intensifying droughts (*very high confidence*) and occasional large floods (*medium confidence*), combined with critical water demands from a growing population, deteriorating infrastructure, and groundwater depletion, suggest the need for flexible water management techniques that address changing risks over time (*high confidence*), balancing declining supplies with greater demands.

Description of evidence base

Research has found that hotter temperatures can make hydrologic droughts more severe. The unprecedented droughts in the Colorado River Basin and California showed that increased temperatures from climate change intensified the severity of the drought.[13,14,56,59] Climate change, more than natural cycles, has reduced snowpack.[46,49] Models project more drought under climate change,[13,56,62] snowpack and streamflow decline in parts of the Southwest, and decreasing surface water supply reliability for cities, agriculture, and ecosystems.[479]

Major uncertainties

Projecting future streamflow and hydrologic characteristics in a basin contains many uncertainties. These differences arise because of uncertainty in temperature and precipitation projections due to differences among global climate models (GCMs), uncertainty in regional downscaling, uncertainty in hydrological modeling, and differences in emissions, aerosols, and other forcing factors. Another important uncertainty is differences in the hemispheric and regional-scale atmospheric circulation patterns produced by different GCMs, which generate different levels of snow loss in different model simulations. A key uncertainty is the wide range in projections of future precipitation across the Southwest;[105] some projections of higher-than-average precipitation in

the northern parts of the Southwest could roughly offset declines in warm-season runoff associated with warming.[105]

Detection is the finding of statistically significant changes different from natural cycles. Attribution is the analysis of the relative contribution of different causes and whether greenhouse gas emissions from human sources outweigh other factors. Attribution of extreme events, such as the recent California drought to climate change, is an area of emerging science. On the one hand, Seager et al. (2015)[58] concluded that the California drought was primarily driven by natural precipitation variability. Sea surface temperature anomalies helped set up the high-pressure ridge over California that blocked moisture from moving inland. On the other hand, Diffenbaugh et al. (2015),[56] Williams et al. (2015),[14] and Berg and Hall (2017)[55] concluded that high temperatures from climate change drove record-setting surface soil moisture deficits that made the drought more severe than it would have been without climate change. Storage of increased precipitation in soils may partially offset increased evaporation, possibly making drought less likely.[480]

In addition to the uncertainties in regional climate and hydrology projections and attribution studies, other uncertainties include potential changes in water management strategies and responses to accommodate the new changing baseline. Additionally, external uncertainties can impact water use in the region via legal, economic, and institutional options for augmenting existing supplies, adding underground storage and recovery infrastructure, and fostering further water conservation, changes in unresolved water rights, and changes to local, state, tribal, regional and national policies related to the balance of agricultural, ecosystem, and urban water use.

Description of confidence and likelihood

The *very high confidence* in historical droughts derives from the detection and attribution analyses of temperature increases, snow decreases, and soil moisture decreases that have documented hydrologic droughts in California and the Colorado River Basin due to anthropogenic climate change and the conclusions of the *Climate Science Special Report* (CSSR), Volume I of the Fourth National Climate Assessment.[74] The *very high confidence* in drought projections derives from the multitude of analyses projecting drought in the Southwest under a range of emissions scenarios and the conclusions of the CSSR.[74] Only *medium confidence* is found for flood projections due to lack of consensus in the model projections of precipitation. Increasingly arid conditions and the potential for increased water use by people lead to an assessment of *high confidence* in the need for new ways to address increasing risks of water scarcity. The actual frequency and duration of water supply disruptions will depend on the preparation of water resource managers with drought and flood plans, the flexibility of water resource managers to implement or change those plans in response to altered circumstances,[481] the availability of funding to make infrastructure more resilient, and the magnitude and frequency of climate extremes.

Key Message 2

Ecosystems and Ecosystem Services

The integrity of Southwest forests and other ecosystems and their ability to provide natural habitat, clean water, and economic livelihoods have declined as a result of recent droughts and wildfire due in part to human-caused climate change (*high confidence*). Greenhouse gas emissions reductions, fire management, and other actions can help reduce future vulnerabilities of ecosystems and human well-being (*high confidence*).

Description of evidence base

Scientific research in the Southwest has provided many cases of detection and attribution of historical climate change impacts. Detection is the finding of statistically significant changes different from natural cycles. Attribution is the analysis of the relative contribution of different causes and whether greenhouse gas emissions from human sources outweigh other factors. Published field research has detected ecological changes in the Southwest and attributed much of the causes of the changes to climate change. Wildfire across the western United States doubled from 1984 to 2015, compared to what would have burned without climate change, based on analyses of eight fuel aridity metrics calculated from observed data, historical observed temperature, and historical modeled temperature from global climate models.[7] The increased heat has intensified droughts in the Southwest,[13,14] reduced snowpack,[49,156] and advanced spring warmth.[101] These changes have dried forests,[154,155] driving the wildfire increase.[7,153] Tree death across the western United States doubled from 1955 to 2007[146] likely due to increased heat,[21] wildfire,[7] and bark beetle infestations,[148,149] all of which are mainly attributable to climate change[7,148,149] more than to other factors such as fire exclusion or competition for light and water.[146] In the Yosemite National Park biome shift,[209] the research analyzed the relative contributions of temperature, precipitation, and the Pacific Decadal Oscillation. The researchers found that "Minimum temperature was the main effect related to accelerating annual branch growth in krummholz whitebark pine and initiation of pine invasion into formerly persistent snowfield openings." In the Yosemite National Park small mammal range shift,[210] the locations of the monitoring sites allowed relative isolation of climate change factors. Moritz et al. (2008)[210] state, "The transect spans YNP [Yosemite National Park], a protected landscape since 1890, and allowed us to examine long-term responses to climate change without confounding effects of land-use change, although at low to mid-elevations there has been localized vegetation change relating to seral dynamics, climate change, or both."

Cutting emissions through energy conservation and renewable energy can reduce ecological vulnerabilities. Under high emissions, projected climate change could triple burned area in the Sierra Nevada, but under low emissions, fire could increase just slightly.[173] Projections of biome shifts[213,215] and wildlife range shifts[217,218,219,220,221] consistently show lower vulnerabilities with lower emissions. Extensive research on, and practice of, fire management show that allowing naturally ignited fires to burn in wilderness and using low-severity prescribed burns can reduce fuels and the risk of high-severity fires under climate change.[181,182,183] Proactive use of fire in Yosemite, Sequoia, and Kings Canyon National Parks has improved the resilience of giant sequoias and other trees to severe fires.[187,188,190,191] Numerous research results have identified climate change refugia for plants and animals.[207,482,483]

Major uncertainties

Because climate model projections often diverge on whether precipitation may increase or decrease, two broad types of fire futures[152] could be 1) dry-fire future—hotter and drier climate, increased fire frequency, fire limited by vegetation, potential biome change of forest to grassland after a fire due to low natural regeneration, and high carbon emissions; or 2) intense-fire future—hotter and wetter climate, more vegetation, increased fire frequency and intensity, fire limited by climate, and higher carbon emissions. These two broad categories each encompass a range of fire conditions. On the ground, gradients of temperature, precipitation, and climate water deficit (difference between precipitation and actual evapotranspiration) generate gradients of fire regimes. Because climate change, vegetation, and ignitions vary across the landscape, potential fire frequency shows high spatial variability. Therefore, future fire types could appear in patches across the landscape, with different fire future types manifesting themselves in adjacent forest patches. Changes in aridity may shift some plant and animal species ranges downslope to favorable combinations of available moisture and suitable temperature, rather than upslope.[484] Plants and animals may respond to changing climate, and have been shown to do so, through range shifts, phenology shifts, biological evolution, or local extirpation. Thus, no single expected response pattern exists.[224]

Description of confidence and likelihood

Field evidence provides *high confidence* that human-caused climate change has increased wildfire, tree death, and species range shifts. Projections consistently indicate that continued climate change under higher emissions could increase the future vulnerability of ecosystems, but that reducing emissions and increasing fire management would reduce the vulnerability, providing *high confidence* in positive benefits of these actions.

Key Message 3

The Coast

Many coastal resources in the Southwest have been affected by sea level rise, ocean warming, and reduced ocean oxygen—all impacts of human-caused climate change (*high confidence*)—and ocean acidification resulting from human emissions of carbon dioxide (*high confidence*). Homes and other coastal infrastructure, marine flora and fauna, and people who depend on coastal resources face increased risks under continued climate change (*high confidence*).

Description of evidence base

At the Golden Gate Bridge, San Francisco, sea level rose 9 ± 0.4 inches (22 ± 1 cm) from 1854 to 2016,[236] and at San Diego, 9 ± 0.8 inches (24 ± 2 cm) from 1906 to 2016.[237] Analyses of these gauges and hundreds around the world show a statistically significant increase in global mean sea level[238,239] due to melting of land ice and expansion of warming water caused by climate change.[21,240] Measurements of sea surface temperatures from buoys off the California coast and around the world, combined with remote sensing data, have found warming of the top 75 m of ocean water at a rate of 2 ± 0.4°F (1.1 ± 0.2°C) per century from 1971 to 2010,[252] caused by climate change.[21] Measurements and modeling of ocean acidity found an increase of acidity in the Pacific Ocean off San Diego of 25% to 40% (0.1 to 0.15 pH units) since 1750,[485] caused by the increase of carbon dioxide

in the atmosphere from cars, power plants, deforestation, and other human activities.[21] Measurements along the California coast have found ocean acidity during the core upwelling season (April to October) increasing by as much as four times (0.7 pH units) to some of the most acidic values in the world.[274] Griggs et al. (2017)[242] project a median sea level rise of 19 inches (49 cm) and a range of 12–29 inches (30–73 cm; 67% probability) for the very low scenario (RCP2.6) and a median of 30 inches (76 cm) and a range of 19–41 inches (49–104 cm; 67% probability) for the higher scenario (RCP8.5) by the end of the century. On a similar timescale, Sweet et al. (2017)[241] provide one map showing sea level rise projections for San Francisco, which shows a 39–47 inch (1–1.2 m) rise for the Intermediate scenario (approximately RCP8.5); the range for all of their scenarios is 0.3–2.5 m. Jevrejeva et al. (2016)[486] project a sea level rise of 73 cm and a range of 12–74 inches (37–187 cm; 5% probability) for the higher scenario (RCP8.5) by 2100.

Major uncertainties

Catastrophic rapid loss of Antarctic and Greenland ice sheets could increase sea level more rapidly. Sea level rise at individual locations depends on the form of the seafloor (bathymetry) and other local conditions. Climate change impacts compound overfishing and make fish populations more vulnerable. Potential economic changes in California's coastal and marine-based economies are subject to many different environmental and socioeconomic factors.

The full complexity of ecological responses to ocean acidification in combination with other stresses in California marine waters is currently unknown. Food supply for marine species,[487] natural variation in resilience,[488,489] and other environmental factors can affect the sensitivity of organisms to acidic conditions.

Description of confidence and likelihood

Field measurements at numerous locations have detected sea level rise, ocean warming, ocean acidification, and ocean hypoxia. Multiple model-based analyses have attributed these changes to human-caused climate change, giving *high confidence* to these impacts of climate change.

Key Message 4

Indigenous Peoples

Traditional foods, natural resource-based livelihoods, cultural resources, and spiritual well-being of Indigenous peoples in the Southwest are increasingly affected by drought, wildfire, and changing ocean conditions (*very likely, high confidence*). Because future changes would further disrupt the ecosystems on which Indigenous peoples depend (*likely, high confidence*), tribes are implementing adaptation measures and emissions reduction actions (*very likely, very high confidence*).

Description of evidence base

Abundant evidence and strong agreement among sources exist regarding current impacts of climate change in the region. Impacts of climate change on the food sources, natural resources-based livelihoods, cultural resources and practices, and spiritual health and well-being of Southwest Indigenous peoples are supported, in part, by evidence of regional temperature

increases,[23,24] drought,[14,56,58,480] declines in snow,[46,49,156] and streamflow,[11,13,60,110] which have affected ecological processes, such as tree death,[146] fire occurrence,[7,152] and species ranges.[211]

Impacts specific to Indigenous peoples include: 1) declining surface soil moisture, higher temperatures, and evaporation converge with oak trees' decreased resilience,[285] diminished acorn production, and fire and pest threat to reduce the availability and quality of acorns for tribal food consumption and cultural purposes;[306] and 2) declining vegetation, higher temperatures, diminished snow, and soil desiccation have caused dust storms and more mobile dunes on some Navajo and Hopi lands, resulting in damaged infrastructure and grazing lands and loss of valued native plant habitat.[44,301,490] Evidence and agreement among evidence exist on the effects of climate-related environmental changes on culturally important foods,[318,319] practices, and mental and spiritual health.[42]

Multiple projections of climate and hydrological changes show potential future change and disruption to the ecosystems on which Indigenous peoples depend for their natural resources-based livelihoods, health, cultural practices, and traditions. These include projections of increased temperatures and heat extremes;[24] longer, more severe, and more frequent drought;[13,65] expanded forest mortality;[197,198] increased wildfire;[172] and ocean temperature increases, ocean acidification, and inundation of coastal areas.[242,273]

Evidence of specific future disruptions to traditional food sources from forests and oceans mostly relies upon inferences, based on projections of changing seasonality and associated phenological or ecosystem responses[298,307] or potential changes to biophysical factors, such as salinity of freshwater lakes, and associated impacts to culturally important fish species.[310]

Abundant evidence exists of autonomous adaptation strategies, projects, and actions, rooted in traditional environmental knowledge and practices or integration of diverse knowledge systems to inform ecological management to support adaptation and ecosystem resilience.[490,491,492,493]

In response to the current and future projected climate changes and ecosystem disruptions, a number of tribes in the Southwest are planning and implementing energy efficient and renewable energy projects.[327,361,494,495] These include installation of or planning for photovoltaic systems,[361] solar arrays, biofuels, microgrids, utility-scale wind, biogas, geothermal heating and cooling systems,[327] increased building insulation,[495] and carbon offsets.[334] Several Southwest tribes, such as the Ramona Band of Cahuilla and the Santa Ynez Band of Chumash Indians, have established or are in the process of establishing energy independence.[495] A well-recognized example is that of the Blue Lake Rancheria Tribe, in California, which was named a Climate Action Champion in 2015–2016 for implementing innovative climate actions, such as an all-of-the-above renewable strategy of transportation, residential, and municipal renewable energy projects, which includes a biogas project. A number of these projects (Ch. 15: Tribes, Figure 15.1) aim to simultaneously meet mitigation and adaptation objectives, such as the Yurok Tribe and the Round Valley Indian Tribe, which have developed carbon offset projects under California's cap-and-trade program to support tribally led restoration and stewardship.[496]

Several tribes in the Southwest are developing climate change adaptation plans to address the current climate-related impacts and prepare for future projected climate changes. The Santa Ynez Band of Chumash Indians, which is working towards an integrated energy and climate action plan,

the Yurok Tribe, the Gila River Indian Community, and the Tohono O'odham Nation are among the first tribes in the region to develop climate adaptation and resilience plans, which reflects a nationwide gap or need for further tribal adaptation plan development. Lack of capacity and funds has hindered progress in moving from planning to implementation, which is similar to the situation for U.S. cities.[497]

Major uncertainties

Uncertainties in the climate and hydrologic drivers of regional changes affecting Indigenous peoples in the Southwest include 1) differences in projections from multiple GCMs and associated uncertainties related to regional downscaling methods, 2) the way snow is treated in regional modeling,[498] 3) variability in projections of extreme precipitation, and, in particular, 4) uncertainties in summer and fall precipitation projections for the region.[88] Additional uncertainties exist in sea level rise projections[242] and, for the California coast, ocean process model projections of acidification, deoxygenation, and warming coastal zone temperatures.[499] For the most part, Native lands lack instrumental monitoring for weather and climate, which is a barrier for long-term climate-related planning.[493]

Complexities arising from the multiple factors affecting ecosystem processes, including tree mortality and fire, often preclude formal detection and attribution studies. Much evidence and agreement among evidence exist regarding the role of hotter temperatures in fire and tree mortality.[7,146] Detection and attribution studies seldom focus explicitly on tribal lands.

Other uncertainties relate to estimating future vulnerabilities and impacts, which depend, in part, on adjudication of unresolved water rights and the potential development of local, state, regional, tribal, and national policies that may promote or inhibit the development and deployment of adaptation and mitigation strategies.

Description of confidence and likelihood

The documented human-caused increase in temperature is a key driver of regional impacts to snow, soil moisture, forests, and wildfire, which affect Indigenous peoples, other frontline communities, and all of civil society. Case study evidence, using Indigenous and Western scientific observations, oral histories, traditional knowledge and wisdom (e.g., Ferguson et al. 2016[493]), suggests that climate change is affecting the health, livelihoods, natural and cultural resources, practices, and spiritual well-being of Indigenous communities and peoples in the Southwest (e.g., Redsteer et al. 2011, 2013; Wotkyns 2011; Cozzetto et al. 2013; Gautam et al. 2013; Navajo Nation Department of Fish and Wildlife 2013; Nania and Cozzetto et al. 2014; Sloan and Hostler 2014; Redsteer and Fordham 2017[44,302,305,307,310,311,490,500,501]). Abundant evidence gives *high confidence* that hotter temperatures, tree mortality, and increased wildfire and drought, due to climate change, would disrupt the ecosystems on which Indigenous people depend; the likelihood of these impacts affecting individual tribes will depend in large part on the non-climatic stresses (such as historical legacies and resource management practices) interacting with the climatic stresses. *Very high confidence* exists that tribes are developing adaptation measures and emissions reductions to address current and future climate change, based on abundant ongoing initiatives and associated documentation.

Key Message 5

Energy

The ability of hydropower and fossil fuel electricity generation to meet growing energy use in the Southwest is decreasing as a result of drought and rising temperatures (*very likely, very high confidence*). Many renewable energy sources offer increased electricity reliability, lower water intensity of energy generation, reduced greenhouse gas emissions, and new economic opportunities (*likely, high confidence*).

Description of evidence base

Numerous studies link Southwest hydrologic drought with a decline in renewable hydroelectricity generation in the region. Hydroelectric generation depends on runoff to fill reservoirs to maximize generation capacity.[336,337] During the California drought, which was intensified by climate change,[14,56] hydroelectric generation in California fell from 43 trillion watt-hours (TWh) in 2011 before the drought to 14 TWh in 2015 during the drought.[335] Climate change also reduced the snowpack[46,47,48,49] and river runoff on which hydroelectric generation depends.[336,337]

Similarly, low reservoir levels in Lake Mead—which is formed by damming the Colorado River—driven by reduced Colorado River runoff[13,59] can reduce the efficiency and production levels of hydropower at Hoover Dam.

Fossil fuel generation efficiency depends on the temperature and availability of the external cooling water. Warming could reduce energy efficiency up to 15% across the Southwest by 2100.[91] Higher temperatures also increase electric resistance in transmission lines, causing transmission losses of 7% under higher emissions.[344] Replacing fossil fuel generation with solar power renewables reduces greenhouse gas emissions and water use per unit of electricity generated.[90] This supports the assertion that increasing solar energy generation in the Southwest could meet the energy demand no longer being met by hydropower and fossil fuel as well as the expected increase in energy use in the future.

Solar energy production is also an economic opportunity for the region. The energy potential for renewable energy is estimated to range from one-third to over ten times 2013 generation levels from all sources.[502] The lower range assumes capacity requirements remain at 2013 levels,[502] but recent data show an upward trend in Southwest energy use.[89]

The high potential for solar energy projects in the Southwest and the extent of federally owned land in the Southwest (well over half the total surface area for the six-state region) prompted the Bureau of Land Management (BLM) and the U.S. Department of Energy to conduct a programmatic environmental impact analysis of a new Solar Energy Program to further support utility-scale solar energy development on BLM-administered lands.[502,503] This potential capacity, combined with the increasingly competitive cost of solar and wind,[504] presents economic opportunities for the region and an opportunity to reduce overall greenhouse gas emissions.

Solar and renewable energy jobs are increasing. The solar workforce increased 25% in 2016, while wind employment increased 32%.[505] Jobs in low-carbon-emission generation systems, including renewables, nuclear, and advanced low-emission natural gas, comprise 45% of all the jobs in the

electric power generation and fuels technologies.[505] Growing Southwest energy use, competitive prices for renewables, and the renewable energy potential of the Southwest favor the replacement of fossil-fuel-generated energy by renewable solar and wind energy.

Major uncertainties

Climate model projections of the future diverge on whether precipitation may increase or decrease for much of the region, so hydroelectric power changes may exhibit spatial variation. The amount of runoff is a key factor driving the generation potential for hydroelectric power. A key uncertainty is how much hydroelectricity generation will decline. Some projections of higher-than-average precipitation in the northern parts of the Southwest could roughly offset declines in warm-season runoff associated with warming.[105]

Energy demand in the Southwest is increasing, but the rate of growth is uncertain.[506] Changes in energy market prices cause future uncertainty in the future mix of energy sources for the Southwest.[502] The low cost of natural gas and the competitive cost of solar and wind renewables make it somewhat certain the proportion of the energy generated from these sources will continue to increase and offset reductions in traditional fossil-fuel-generated energy, reducing overall greenhouse gas emissions.[504] Renewable energy job growth potential is also uncertain and depends on the factors mentioned above.[505]

Additionally, daily to multiyear variation in coastal cloud cover affects solar electricity generation potential along the California coast.[507,508,509,510]

Description of confidence and likelihood

Hydrological drought in California reduced hydroelectric generation[335] and fossil fuel electricity generation efficiencies. Drought and rising temperatures under climate change can reduce the ability of hydropower and fossil fuel electricity generation to meet growing energy use in the Southwest (*very likely*, *very high confidence*). Renewable solar and wind energy offers increased electricity reliability, lower water intensity for energy generation, reduced greenhouse gas emissions, and new economic opportunities (*likely*, *high confidence*).

Key Message 6

Food

Food production in the Southwest is vulnerable to water shortages (*medium confidence*). Increased drought, heat waves, and reduction of winter chill hours can harm crops (*medium confidence*) and livestock (*high confidence*); exacerbate competition for water among agriculture, energy generation, and municipal uses (*medium confidence*); and increase future food insecurity (*medium confidence*).

Description of evidence base

Climate change has altered climate factors fundamental to food production and rural livelihoods in the Southwest. Abundant evidence and good agreement in evidence exist regarding regionally increasing temperatures, reduced soil moisture, and effects on regional snowpack and surface water sources.[13,23,67,74,79] The heat of climate change has intensified severe droughts in California[14,56]

and the Colorado River Basin.[13] Hotter temperatures and aridity in the Southwest affected agricultural productivity from 1981 to 2010.[366]

Elevated temperatures can be associated with failure of some crops, such as warm-season vegetable crops, and reduced yields and/or quality in others.[374] Temperatures in California, Nevada, and Arizona are already at the upper threshold for corn[372] and rice.[373] While crops grown in some areas might not be viable under hotter conditions, other crops such as olives, cotton, kiwi, and oranges may replace them.[375] In the Southwest, climate change may cause a northward shift in crop production, potentially displacing existing growers and affecting rural communities.[376] Quality of specialty crops, both nutritive and sensory, declines because of increased temperatures and other changes associated with a changing climate,[393,511] which is particularly important in a region producing a majority of the Nation's specialty crops. Decreases in winter chill hours may reduce fruit and tree nut yields, though the magnitude may vary considerably.[380,381]

High ambient temperatures associated with climate change could decrease production of rangeland vegetation across the Southwest,[384] reducing available forage for livestock. Ranching enterprises across the region have vastly different characteristics that will influence their adaptive capacities.[390]

Local-scale impacts can vary considerably across the region depending upon surface and groundwater availability. Drought causes altered water management, with heavy reliance on a limited groundwater to sustain regional food production.[130] Despite severe localized impacts, losses in total agricultural revenue are buffered by groundwater reliance to offset surface water shortage.[369] Parts of the Southwest have exhausted sustainable use of groundwater resources. When surface water supplies are reduced, farmers shift to increased groundwater pumping, even when pumping raises production costs[371]—declining groundwater tables significantly increase pumping costs and require drilling of deeper wells.[130] Continued climate change may reduce aquifer recharge in the southern part of the region 10%–20%.[370] Climate change is projected to cause longer and more severe drought periods that will intensify the uncertainty associated with Southwest water supply and demand. Water-intensive forage crops and the livestock industry are especially vulnerable to climate-related water shortages.[15]

Major uncertainties

The impacts of climate change on food production depend upon microclimatology and local-scale environmental, social, and economic resources. While the scientific community relies upon computer models and generalized information to project likely future conditions, unforeseen consequences of warming temperatures, such as those related to pests, pollinators, and pathogens, may be more detrimental than some of the well-documented projections, such as temperature impacts on reduced yields. The effects of increased precipitation supplying the deep root zone may somewhat offset the increase in temperature, so agricultural drought may be less frequent for trees and other crops dependent on deeper soil moisture.[480] Scientists are producing more drought- and heat-tolerant cultivars, which may be suitable to production in the projected warmer and more arid climate of the Southwest.

Since food security relies on complex national and international trade networks, how regional climate change may affect local food security is uncertain. Many adaptation options, such as using

alternate breeds, crops, planting and harvest dates, and new (sometimes untested) chemicals, may work in certain situations but not others. Thus, predicting impacts to food production in a hotter/drier land is likely to vary by crop and location, necessitating flexibility and adaptive management. Of paramount uncertainty is the impact of water shortage on regional food production as other uses may outcompete producers for limited supplies.

Description of confidence and likelihood

Since the availability of affordable food around the world depends upon complex trade and transportation networks, the effects of climate change on Southwest food availability, production, and affordability remain highly complex and thereby uncertain and classified with *medium confidence*. While the viability of rural livelihoods is vulnerable to water shortages and other climate-related risks, rural livelihoods may be supplemented by other nonagricultural income, such as recreation and hunting. The viability of rural livelihoods is highly complex, and risk is, therefore, classified with *medium confidence*. Crop impacts related to hotter and drier conditions and reduced winter chill periods, caused by climate change, are classified with *medium confidence*. Not all crops are directly harmed by warming temperatures, and the simulation impacts of reduced chilling hours can produce a fairly wide range of results depending upon model assumptions. Hotter and drier conditions can directly harm livestock via reduced forage quantity and quality and exposure to higher temperatures, conferring a *high confidence* classification. Projections of future drought and water scarcity portend increased competition for water from other beneficial uses with *medium confidence*.

Key Message 7

Human Health

Heat-associated deaths and illnesses, vulnerabilities to chronic disease, and other health risks to people in the Southwest result from increases in extreme heat, poor air quality, and conditions that foster pathogen growth and spread (*high confidence*). Improving public health systems, community infrastructure, and personal health can reduce serious health risks under future climate change (*medium confidence*).

Description of evidence base

Strong evidence and good agreement among multiple sources and lines of evidence exist, indicating that the Southwest regional temperature may increase, snowpack may decline, soil moisture may decrease, and drought may be prolonged.[14,23,24,56,58,62,68,74,480]

Exposure to hotter temperatures and extreme heat events, partly a manifestation of human-caused climate change, already led to heat-associated deaths and illnesses in heat waves in Arizona and California in the early and mid-2000s.[398,399,400,401,402,406,444,450,512]

Good agreement exists among models that most of the Southwest may become more arid, due to the effect of increasing temperatures on snow, evaporation, and soil moisture.[58,65,70,80] Projections also indicate that flood-causing atmospheric rivers may become more moist, frequent, and intense[84,85,86] and that intense daily precipitation may increase in frequency.[88,513] Models project

declines in future runoff of key Southwest rivers, such as the Colorado, due chiefly to the effects of increased temperature on soil moisture and snowpack.[13,71,110]

Strong evidence exists of the effects of extreme heat on public health in the region (e.g., Knowlton et al. 2009, Oleson et al. 2015, Wilhelmi et al. 2004[400,514,515]) and for reasonable projections of future deaths and costs of lost labor productivity due to enhanced future episodes of extreme heat. Factors that predict a person will be at increased risk include being confined to bed, not leaving home daily, and being unable to care for oneself;[516] various general indicators of being socially isolated (such as living alone, the presence of or frequency of social contacts, or being isolated linguistically);[516,517,518,519] and persons who are socioeconomically disadvantaged.[516,517,518,519] Dehydration in general and dehydration associated with medications (neurological and non-neurological) that impair thermoregulation or thirst regulation were also associated with elevated risk of mortality during the 2003 heat wave in France.[520] The role of prescription medications in altering the risk for heat-associated illness or death is of growing interest and concern.[521] This issue is more important as chronic diseases become more prevalent and more people take prescription drugs.

Given the proportion of the U.S. population in the Southwest, a disproportionate number of West Nile virus, plague, hantavirus pulmonary syndrome, and Valley fever cases occur in the region.[158,420] West Nile virus transmission is projected to shift to the north under climate change, and areas where the mosquitoes that carry this virus are present may see increased abundances.[441,442,443] The mosquito species that carry Zika and chikungunya are established in parts of the region, but mosquito-borne transmission has only been observed in Puerto Rico, the U.S. Virgin Islands, Florida, and Texas (Ch. 14: Human Health).

Overall, the Southwest is ill-prepared to absorb the additional patient load that would accompany climate change associated disasters.[448] The American College of Emergency Physicians assigned an overall emergency care grade of C or C+ to three of the six Southwest states, with the others receiving poorer grades, and four of the six states received an F grade for access to emergency care.[448]

Major uncertainties

Uncertainties in the climate and hydrologic drivers of regional changes affecting public health include 1) differences in projections from multiple GCMs and associated uncertainties related to regional downscaling methods, 2) variability in projections of extreme precipitation, 3) uncertainties in summer and fall precipitation projections for the region,[88] and 4) uncertainties in models that project occurrence and levels of climate-sensitive exposures that are known to impact public health, such as local and regional ozone air pollution, particulate air pollution (for example, increases from wildfire emissions or reductions from advancements in vehicle emissions control technology), or occurrence and exposure to toxins or pathogens.

Studies of non-fatal illnesses using healthcare services data can yield critical insights different from those one can derive from death data. Most studies of heat impacts on health have focused on deaths rather than nonfatal illnesses. This is primarily because hospitalization and emergency department data, compared with death certificate data, are not as available or uniform across locations, and when they are available it can be difficult to access them due to concerns for patient confidentiality. Ongoing enhancements to electronic medical records technology and

adoption across the healthcare services sector will potentially address those limitations in the near future and will provide invaluable data resources to identify and adopt prevention strategies that reduce the vulnerability of patients and populations to the adverse effects of climate-sensitive exposures.

More recent work focusing on the more deadly neuroinvasive West Nile virus indicates that regionally, the central and southern parts of the country may experience increasing cost from this vector-borne disease in the future.[178,440] The lack of a statistical association between temperature and West Nile virus diagnoses in the Southwest may be because extreme temperatures in some locations rise above the survival thresholds for vectors, thereby reducing mosquito abundance[522,523] and disease transmission.[419] Additionally, because the data for diseases like Valley fever are limited to cases, rather than exposures, the link to climate change is not clear.[435,436]

While improvements to individual health and to clinical and community infrastructure are highly likely to 1) improve physical capacity to adapt to climate effects, 2) diminish the overall impacts on population health, and 3) increase societal capacity to respond quickly to dampen the effects of long-term and emergency responses,[446,447,524] other factors also influence adaptive capacity, adding considerable uncertainty. For example, many factors influence the observed number of West Nile virus cases including available habitat, human prevention and control efforts, and recent history of cases in a given area.[442,525,526,527]

Description of confidence and likelihood

Evaluation of confidence levels for the assessment of the type and magnitude of observed or projected public health and clinical impacts was based on the strength of evidence underlying the answers to three primary questions:

1. What characteristics of the region's historical climate and weather patterns translate directly (for example, extreme heat) or indirectly (for example, higher temperatures fostering ozone formation or the growth and spread of pathogens and vectors) to exposures associated with observed human health risks that are unique to or overrepresented in the Southwest?

2. Does recent historical evidence indicate that climate and weather patterns have changed, or do climate models project changes over the 21st century, thereby increasing the risk of human exposures and health impacts evaluated under question 1?

3. What are the determinants of individual and population vulnerability that increase or decrease the risk of an adverse health outcome or affect adaptive capacity? These include factors that affect a) biological susceptibility, b) physical environment and exposure characteristics, and c) social, behavioral, or economic factors.

To the extent possible, the evaluation recognized and accounted for the complex interconnections among these factors, the fact that their relative importance may differ across geographic and temporal scales, and the combined uncertainties of evidence from multiple disciplines (for example, health sciences, climatology, and social or behavioral sciences) that can vary substantially.

The information revealed by answering those questions, gives *high confidence* that extreme heat will be the dominant driver of exposures that pose the greatest health risks in the

Southwest—including direct effects of heat on individuals and indirect effects of heat on air pollution levels. Due to the uncertainties related to the frequency and intensity of human exposures and related to impacts on essential ecosystem services under projected climate change, the statement "Improving public health systems, community infrastructure, and personal health can reduce serious health risks under future climate change" is made with *medium confidence*. Nevertheless, clinical and public health policy effectiveness assessments show that such improvements can reduce the burden of disease and health risks associated with environmental exposures.

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26 Alaska

Anchorage, Alaska

Key Message 1

Marine Ecosystems

Alaska's marine fish and wildlife habitats, species distributions, and food webs, all of which are important to Alaska's residents, are increasingly affected by retreating and thinning arctic summer sea ice, increasing temperatures, and ocean acidification. Continued warming will accelerate related ecosystem alterations in ways that are difficult to predict, making adaptation more challenging.

Key Message 2

Terrestrial Processes

Alaska residents, communities, and their infrastructure continue to be affected by permafrost thaw, coastal and river erosion, increasing wildfire, and glacier melt. These changes are expected to continue into the future with increasing temperatures, which would directly impact how and where many Alaskans will live.

Key Message 3

Human Health

A warming climate brings a wide range of human health threats to Alaskans, including increased injuries, smoke inhalation, damage to vital water and sanitation systems, decreased food and water security, and new infectious diseases. The threats are greatest for rural residents, especially those who face increased risk of storm damage and flooding, loss of vital food sources, disrupted traditional practices, or relocation. Implementing adaptation strategies would reduce the physical, social, and psychological harm likely to occur under a warming climate.

Key Message 4

Indigenous Peoples

The subsistence activities, culture, health, and infrastructure of Alaska's Indigenous peoples and communities are subject to a variety of impacts, many of which are expected to increase in the future. Flexible, community-driven adaptation strategies would lessen these impacts by ensuring that climate risks are considered in the full context of the existing sociocultural systems.

Key Message 5

Economic Costs

Climate warming is causing damage to infrastructure that will be costly to repair or replace, especially in remote Alaska. It is also reducing heating costs throughout the state. These effects are very likely to grow with continued warming. Timely repair and maintenance of infrastructure can reduce the damages and avoid some of these added costs.

Key Message 6

Adaptation

Proactive adaptation in Alaska would reduce both short- and long-term costs associated with climate change, generate social and economic opportunity, and improve livelihood security. Direct engagement and partnership with communities is a vital element of adaptation in Alaska.

Executive Summary

Alaska is the largest state in the Nation, almost one-fifth the size of the combined lower 48 United States, and is rich in natural capital resources. Alaska is often identified as being on the front lines of climate change since it is warming faster than any other state and faces a myriad of issues associated with a changing climate. The cost of infrastructure damage from a warming climate is projected to be very large, potentially ranging from $110 to $270 million per year, assuming timely repair and maintenance. Although climate change does and will continue to dramatically transform the climate and environment of the Arctic, proactive adaptation in Alaska has the potential to reduce costs associated with these impacts. This includes the dissemination of several tools, such as guidebooks to support adaptation planning, some of which focus on Indigenous communities. While many opportunities exist with a changing climate, economic prospects are not well captured in the literature at this time.

As the climate continues to warm, there is likely to be a nearly sea ice-free Arctic

during the summer by mid-century. Ocean acidification is an emerging global problem that will intensify with continued carbon dioxide (CO_2) emissions and negatively affects organisms. Climate change will likely affect management actions and economic drivers, including fisheries, in complex ways. The use of multiple alternative models to appropriately characterize uncertainty in future fisheries biomass trajectories and harvests could help manage these challenges. As temperature and precipitation increase across the Alaska landscape, physical and biological changes are also occurring throughout Alaska's terrestrial ecosystems. Degradation of permafrost is expected to continue, with associated impacts to infrastructure, river and stream discharge, water quality, and fish and wildlife habitat.

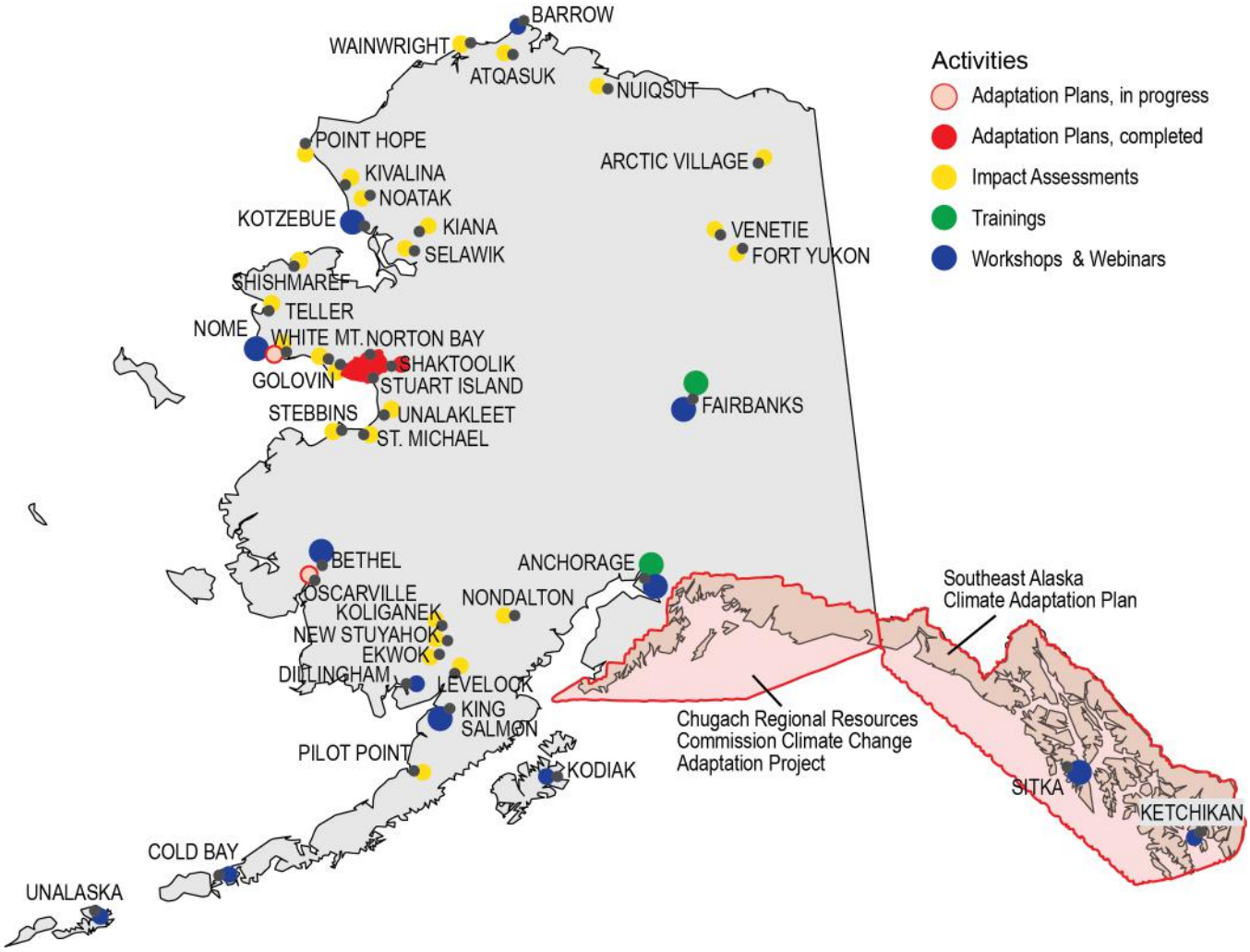
Longer sea ice-free seasons, higher ground temperatures, and relative sea level rise are expected to exacerbate flooding and accelerate erosion in many regions, leading to the loss of terrestrial habitat in the future and in some cases requiring entire communities or portions of communities to relocate to safer terrain. The influence of climate change on human health in Alaska can be traced to three sources: direct exposures, indirect effects, and social or psychological disruption. Each of these will have different manifestations for Alaskans when compared to residents elsewhere in the United States. Climate change exerts indirect effects on human health in Alaska through changes to water, air, and soil and through ecosystem changes affecting disease ecology and food security, especially in rural communities.

Alaska's rural communities are predominantly inhabited by Indigenous peoples who may be disproportionately vulnerable to socioeconomic and environmental change; however, they also have rich cultural traditions of resilience and adaptation. The impacts of climate change will likely affect all aspects of Alaska Native societies, from nutrition, infrastructure, economics, and health consequences to language, education, and the communities themselves.

The profound and diverse climate-driven changes in Alaska's physical environment and ecosystems generate economic impacts through their effects on environmental services. These services include positive benefits directly from ecosystems (for example, food, water, and other resources), as well as services provided directly from the physical environment (for example, temperature moderation, stable ground for supporting infrastructure, and smooth surface for overland transportation). Some of these effects are relatively assured and in some cases are already occurring. Other impacts are highly uncertain, due to their dependence on the structure of global and regional economies and future human alterations to the environment decades into the future, but they could be large.

In Alaska, a range of adaptations to changing climate and related environmental conditions are underway and others have been proposed as potential actions, including measures to reduce vulnerability and risk, as well as more systemic institutional transformation.

Adaptation Planning in Alaska



The map shows tribal climate adaptation planning efforts in Alaska. Research is considered to be adaptation under some classification schemes.[1,2] Alaska is scientifically data poor, compared to other Arctic regions.[3] In addition to research conducted at universities and by federal scientists, local community observer programs exist through several organizations, including the National Weather Service for weather and river ice observations;[4] the University of Alaska for invasive species;[5] and the Alaska Native Tribal Health Consortium for local observations of environmental change.[6] Additional examples of community-based monitoring can be found through the website of the Alaska Ocean Observing System.[7] *From Figure 26.9 (Source: adapted from Meeker and Kettle 2017[8]).*

Background

Alaska is the largest state in the Nation, spanning a land area of around 580,000 square miles, almost one-fifth the size of the combined lower 48 United States. Its geographic location makes the United States one of eight Arctic nations. The State has an abundance of natural resources and is highly dependent on oil, mining, fishing, and tourism revenues. Changes in climate can have positive and negative impacts on these resources.[9,10,11]

As part of the Arctic, Alaska is on the front lines of climate change[12,13] and is among the fastest warming regions on Earth (Ch. 2: Climate, KM 7).[14] It is warming faster than any other state, and it faces a myriad of issues associated with a changing climate. The retreat of arctic sea ice affects many Alaskans in different ways, such as through changes in fish and wildlife habitat that are important for subsistence, tourism, and recreational activities.[15,16] The warming of North Pacific waters can contribute to the northward expansion of marine fish species, ecosystem changes, and potential relocation of fisheries.[17] An ice-free Arctic also contributes to increases in ocean acidification (through greater ocean–atmosphere interaction), affecting marine mammal habitat and the growth and survival of fish and crab species that are important for both personal and commercial use.[18] Lack of sea ice also contributes to increased storm surge and coastal flooding and erosion, leading to the loss of shorelines and causing some communities to relocate.[19]

Thawing permafrost, melting glaciers, and the associated effects on Alaska's infrastructure and hydrology are also of concern to Alaskans. Thawing permafrost has negatively affected important infrastructure, which is costly to repair, and these costs are projected to increase.[20,21] Melting glaciers may affect hydroelectric power generation through changes in river discharge and associated changes in reservoir capacity.[22] A warming climate is also likely to increase the frequency and size of wildfires, potentially changing the type and extent of wildlife habitat favorable for some important subsistence species.[23,24,25] Climate change also brings a wide range of human health threats to Alaskans due to increased injuries, smoke inhalation, damage to vital infrastructure, decreased food and water security, and new infectious diseases.[10] The subsistence activities of local residents are also affected, which in turn affects food security, culture, and health.[26,27,28,29]

The cost of a warming climate is projected to be huge, potentially ranging from $3 to $6 billion, between 2008 and 2030 (in 2008 dollars; $3.3–$6.7 billion in 2015 dollars). There are, however, a number of opportunities for Alaskans to respond to these climate-related challenges, including several tools and guidebooks available to support adaptation planning, with some focused specifically on Indigenous communities.[30] While many opportunities exist with a changing climate, economic prospects are not well captured in the literature at this time.

Climate

The rate at which Alaska's temperature has been warming is twice as fast as the global average since the middle of the 20th century. Statewide average temperatures for 2014–2016 were notably warmer as compared to the last few decades,[31,32,33] with 2016 being the warmest on record. Daily record high temperatures in the contiguous United States are now occurring twice as often as record low temperatures. In Alaska, starting in the 1990s, high temperature records occurred three times as often as record lows, and in 2015, an astounding nine times as frequently.[34,35]

Statewide annual average temperatures from 1925 to the late 1970s were variable with no clear pattern of change;[36] however, beginning in the late 1970s and continuing at least through the end of 2016, Alaska statewide annual average temperatures began to increase, with an average rate of 0.7°F per decade, (Taylor et al. 2017,[37] after Hartmann and Wendler 2005;[38] see Figure 26.1). Temperatures have been increasing faster in Arctic Alaska than in the temperate southern part of the state, with the Alaska North Slope warming at 2.6 times the rate of the continental U.S. and with many other areas of Alaska, most notably the west coast, central interior, and Bristol Bay, warming at more than twice the continental U.S. rate.[39] The long-term temperature trends, however, include considerable variability from decade to decade. For example, in the early part of the record (1920s to early 1940s), temperatures were moderate statewide, with annual averages generally near the long-term average, but were lower from about 1945 to about 1976 and then increased rapidly in the 1970s and 1980s and again in the mid-2010s (Figure 26.1). These variations are in part consistent with variations in large-scale patterns of climate variability in the Pacific Ocean;[40] in particular, Arctic warming in the early 20th century was intensified by Pacific variability (warm and cold anomalies of the Pacific sea surface temperatures).[41] Precipitation changes have

Observed and Projected Changes in Annual Average Temperature

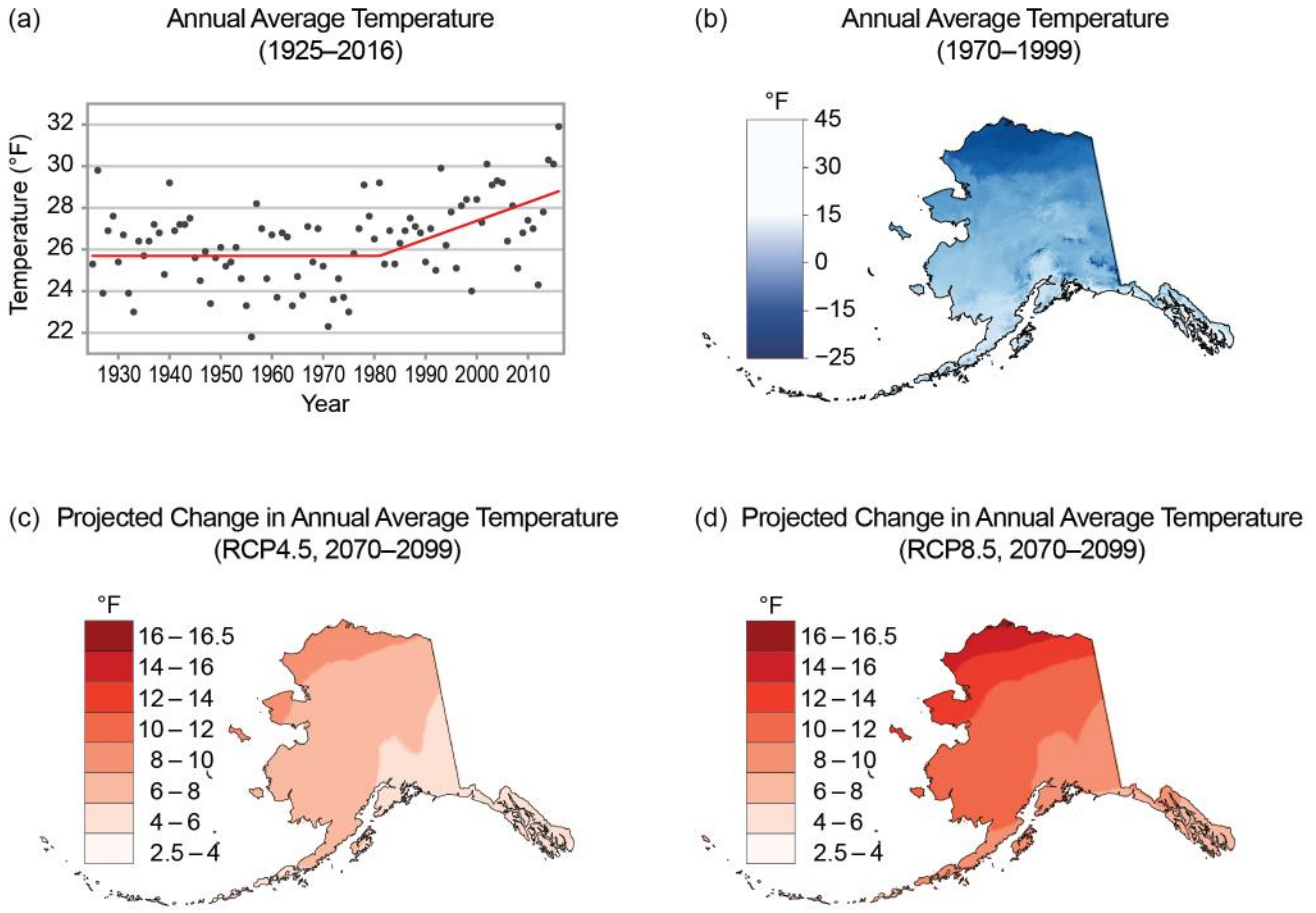


Figure 26.1: (a) The graph shows Alaska statewide annual average temperatures for 1925–2016. The record shows no clear change from 1925 to 1976 due to high variability, but from 1976–2016 a clear trend of +0.7°F per decade is evident. (b) The map shows 1970–1999 annual average temperature. Alaska has a diverse climate, much warmer in the southeast and southwest than on the North Slope (c) The map shows projected changes from climate models in annual average temperature for end of the 21st century (compared to the 1970–1999 average) under a lower scenario (RCP4.5). (d) The map is the same as (c) but for a higher scenario (RCP8.5). Sources: (a) National Oceanic and Atmospheric Administration and U.S. Geological Survey, (b–d) U.S. Geological Survey.

varied significantly across the state from 1920 to 2012, with long-term trends generally showing no clear pattern of change.[39]

Projected Temperature and Precipitation Changes

Recent availability of more localized climate information allows for more complete descriptions of the geographical variation in historical trends and climate projections.[39,42,43] Using downscaled global climate models[43] and the higher scenario (RCP8.5) (see Ch. 2: Climate, Box 2.7 and the Scenario Products section of App. 3),[44] more warming is projected in the Arctic and interior areas than in the southern areas of Alaska, and average annual precipitation increases are projected for all areas of the state, with greater increases in the Arctic and interior and the largest increases in the northeastern interior.

Climatic extremes are expected to change with the changing climate. Under a higher scenario (RCP8.5), by mid-century (2046–2065) the highest daily maximum temperature (the hottest temperature one might expect on a given summer day) is projected to increase 4°–8°F compared to the average for 1981–2000. For the same future period (2046–2065), the lowest daily maximum temperature (the highest temperature of the coldest day of the year) throughout most of the state is projected to increase by more than 10°F, with smaller projected changes in the Aleutian Islands and southeastern Alaska. Additionally, the lowest daily minimum temperatures (the coldest nights of the year) are projected to increase by more than 12°F. The number of nights below freezing would likely decrease by at least 20 nights per year statewide, and by greater than 45 nights annually in coastal areas of the North Slope, Seward Peninsula, Yukon–Kuskokwim Delta, Alaska Peninsula, and Southcentral Alaska.[45] Annual maximum one-day precipitation is projected to increase by 5%–10% in southeastern Alaska and by more than 15% in the rest of the state, although the longest dry and wet spells are not expected to change over most of the state.[45] Growing season length (the time between last and first frosts in a given year) is expected to increase by at least 20 days and perhaps more than 40 days compared to the 1982–2010 average.[35] Whether or not this increased growing potential is realized will largely depend on soil conditions and precipitation.

Key Message 1

Marine Ecosystems

Alaska's marine fish and wildlife habitats, species distributions, and food webs, all of which are important to Alaska's residents, are increasingly affected by retreating and thinning arctic summer sea ice, increasing temperatures, and ocean acidification. Continued warming will accelerate related ecosystem alterations in ways that are difficult to predict, making adaptation more challenging.

Arctic sea ice—its presence or absence and year-to-year changes in extent, duration, and thickness—in conjunction with increasing ocean temperatures and ocean acidification, affects a number of marine ecosystems and their inhabitants, including marine mammals, the distribution of marine Alaska fish and their food sources.[37]

Arctic Sea Ice Continues to Change

Since the early 1980s, annual average arctic sea ice extent has decreased between 3.5% and 4.1% per decade, and September sea ice extent, which is the annual minimum extent, has decreased between 10.7% and 15.9% per decade. As the climate continues to warm, it is likely that there will be a sea ice-free Arctic during the summer within this century.[37,46]

Sea ice provides an important surface for algal production and growth in marine ecosystems during spring. This production beneath the sea ice is an important source of carbon for pelagic (mid- to upper-water column) grazers, such as copepods and krill, and for benthic (lower-water) detritivores, such as clams and worms that feed on dead, organic material.[47,48] In turn, the abundance of these animals provides food for higher trophic-level organisms such as fish, birds, and mammals in regional marine ecosystems. The presence or absence of sea ice affects the transfer of heat, water temperature, and nutrient transport, as well as other processes (such as the breakdown or transformation of organic matter into its simplest inorganic forms) that affect ecosystem productivity.[49] In the Arctic, higher-level organisms such as Arctic cod,[17] polar bears, and walruses[50,51,52,53] are dependent upon sea ice for foraging, reproduction, and resting and are directly affected by sea ice loss and thinning (Box 26.1).

Box 26.1: Polar Bears and Walruses

Polar bears and walruses are both dependent on sea ice during parts of their lives. Polar bears rely on sea ice to access prey and establish maternal dens, and Pacific walruses rely on drifting sea ice as a platform to rest on between foraging dives. Changes in the distribution of seasonal sea ice have resulted in changes in the behavior, migration, distribution, and, in some areas, population dynamics of both species. Changes in spring ice melt have affected the ability of Alaska coastal communities to meet their walrus harvest needs, resulting in low harvest levels in several recent years. Ongoing research seeks to forecast the population-level consequences of sea ice changes for polar bears and walruses by studying the animals' behavior changes, especially in response to increased shipping and changes in subsistence harvest practices. Changes in the ability of Indigenous communities to access these two species in the future may be harder to assess, but that access will be crucial for the short- and long-term hunting success and resultant well-being of the communities.

Figure 26.2: (a) An adult female polar bear and cub are shown near Kaktovik, Alaska, in September 2015. (b) Walruses gathered on the shores of the Chukchi Sea near Point Lay, Alaska, in September 2013. Photo credits: (a) Stewart Breck, USDA (b) Ryan Kingsbery, USGS.

Ocean Acidification

The oceans are becoming more acidic (known as ocean acidification) in an emerging global problem that will intensify with continued carbon dioxide (CO_2) emissions (Ch. 9: Oceans, KM 1 and 2). Ocean acidification negatively affects organisms such as corals, crustaceans, crabs, mollusks, and other calcium carbonate-dependent organisms such as pteropods (free-swimming pelagic sea snails and sea slugs), the latter being an important part of the food web in Alaska waters. Some studies in the nutrient-rich regions have found that food supply may play a role in determining the resistance of some organisms to ocean acidification.[54]

Changes in ocean chemistry and increased corrosiveness are exacerbated by sea ice melt, respiration of organic matter, upwelling, and glacial runoff and riverine inputs, thus making the high-latitude North Pacific and the western Arctic Ocean (and especially the continental shelves of the Bering, Chukchi, and Beaufort Seas; see Figure 26.3) particularly vulnerable to the effects of ocean acidification. Also, more ice-free water will indirectly allow for greater uptake of atmospheric CO_2.[18,55,56] More recent research suggests that corrosive conditions have been expanding deeper into the Arctic Basin over the last several decades.[57] The annual average aragonite saturation state (a metric used to assess ocean acidification) for the Beaufort Sea surface waters likely crossed the saturation horizon near 2001),[18] meaning that the Beaufort Sea is undersaturated (lacking sufficient concentrations of aragonite) most of the year—a condition that limits the ability of many marine species to form shells or skeletons (Figure 26.3). Under the higher scenario (RCP8.5), the Chukchi Sea is projected to first cross this threshold around 2030 and then remain under the threshold after the early 2040s, and the Bering Sea will likely cross and remain under the threshold around 2065 (Figure 26.3).[18]

Through lab experiments, ocean acidification has been shown to affect the growth, survival, sensory abilities, and behavior of some species, especially species of importance to Alaska, such as Tanner and red king crab and pink salmon.[58,59,60,61,62] Studies indicate flatfish, such as the northern rock sole, are sensitive to lowered pH (lower pH equates to higher acidity), while walleye pollock have not shown adverse effects on growth or survival.[63,64] Pteropods play a critically important role in the Alaska water food web and have been shown to be particularly susceptible to ocean acidification. The effect of ocean acidification on pteropods manifests itself as severe shell dissolution, impaired growth, and also reduced survival.[65,66] More importantly, these effects are observed in the natural environment, making pteropods one of the most susceptible indicators for ocean acidification.[65,67,68] The effects observed in pteropods can be interpreted as the early-warning signal of the impacts of ocean acidification on the ecosystem integrity, linking pteropod effects to higher trophic levels, in particular fish (such as pink salmon, sole, and herring) that are feeding on pteropods. However, the impacts on these food webs are highly uncertain[69,70,71] but can be more detrimental in the high-latitudinal ecosystems with fewer species and shorter food chains.[67,68]

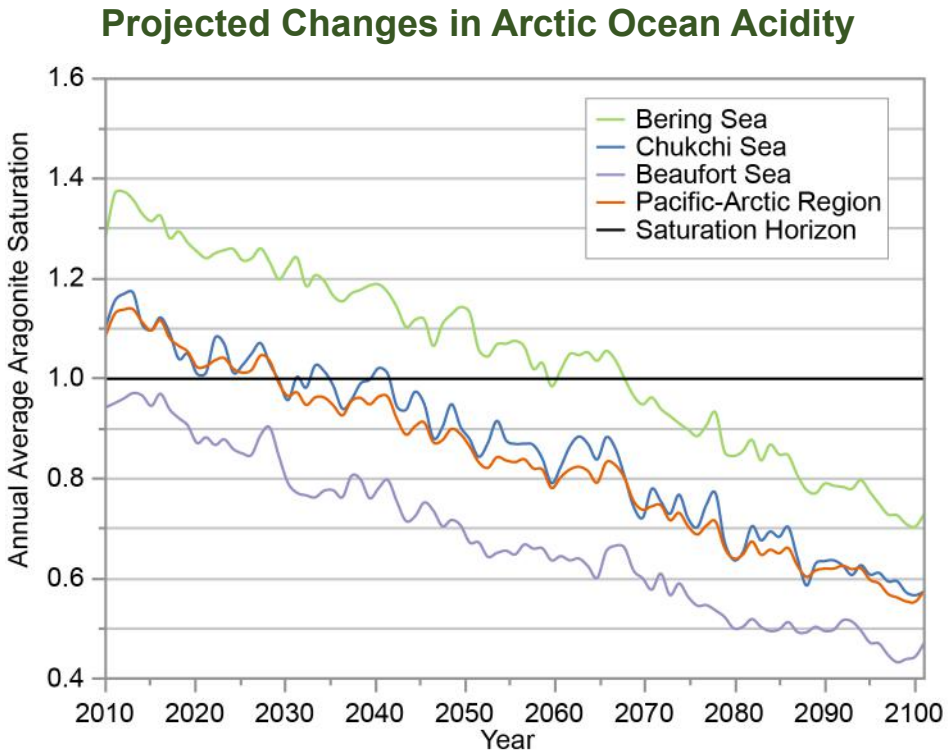


Figure 26.3: The time series shows the projected decline in the annual average aragonite saturation (one of the consequences of increased ocean acidity, or lower pH) for the Bering Sea, Chukchi Sea, Beaufort Sea, and for the entire Pacific-Arctic region under the higher scenario (RCP8.5). Aragonite saturation is a metric used to assess ocean acidification and the ability for organisms to build shells and skeletons. The annual average saturation state for the Beaufort Sea surface waters likely crossed the saturation horizon—a tipping point—around 2001, meaning it is currently undersaturated and its marine ecosystems are vulnerable to the impacts of ocean acidification during most of the year. The Chukchi Sea is projected to first cross this threshold around 2030 and then likely remain under the threshold after the early 2040s; the Bering Sea is projected to be a concern after 2065. Source: adapted from Mathis et al. 2015.[18]

Alaska Fishes

More than 600 fish species have been found in Alaska waters,[72] and Alaska's industrial fisheries in the Gulf of Alaska and Bering Sea are among the most productive and valuable in the world, with an estimated average of $5.9 billion of total economic activity in 2013–2014 (in 2013–2014 dollars).[73,74] Climate effects on Alaska's marine ecosystems are of considerable economic interest because of their impacts on the commercial harvests from the Northeast Pacific and subsistence fisheries for salmon, char, whitefishes, and ciscos in the Arctic and on these species or others elsewhere in the state.

The distribution of many ocean fish species is shifting northward as the ranges of warmer-water species expand and colder-water species contract in response to rising ocean temperatures (Ch. 9: Oceans, KM 2), with the confirmed presence of 20 new species and 59 range changes in the last 15 years in the Chukchi and Beaufort Seas.[17] In the Bering Sea, Alaska pollock, snow crab, and Pacific halibut have generally shifted away from the coast and farther from shore since the early 1980s.[75] These changes reflect possible northward shifts in species distributions, particularly in the Bering Strait region.[76]

Marine ecosystem food webs are also being affected by climate change. Changes in sea ice cover and transport of warmer seawater and drifting organisms (such as plankton, bacteria, and marine algae) may be impacting how surface ocean waters interact with the bottom ocean waters, especially over the shallow northern Bering and Chukchi Sea

Changes to North Pacific Marine Ecosystems in a Warming Climate

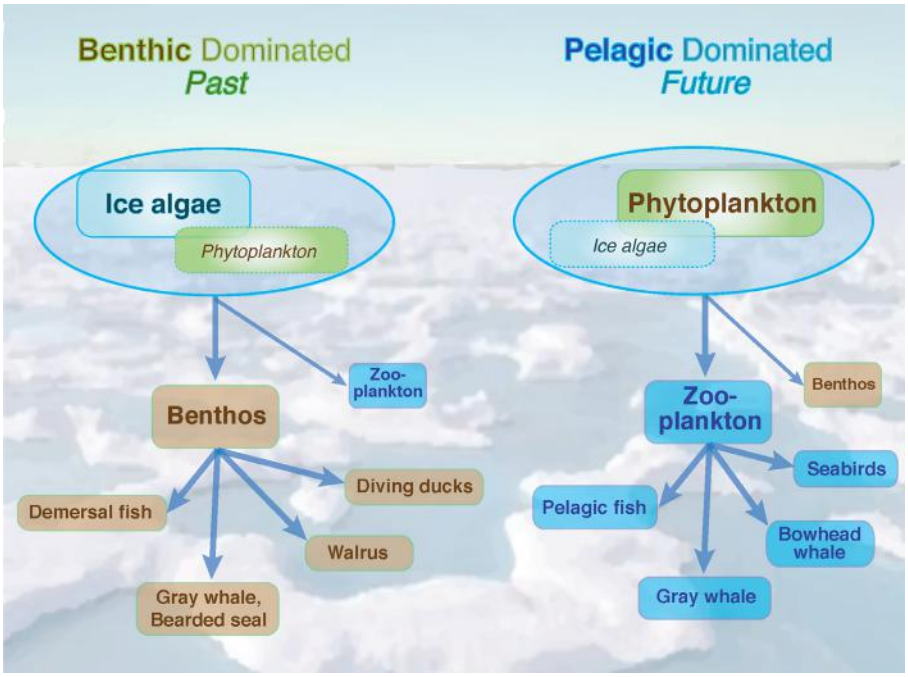


Figure 26.4: As sea ice thins and retreats earlier in the season, it is anticipated that food webs under the ice will switch from a benthic-dominated (lower in the water to seafloor) to a pelagic-dominated (middle to higher in the water) marine ecosystem. Source: Moore and Stabeno 2015.[78]

shelves. As relatively larger organisms (such as zooplankton, which are very tiny marine animals in the water column) become more abundant, they are able to efficiently graze on the smaller plant organisms (such as phytoplankton—microscopic marine plants) and reduce the amount of food supplied to the bottom sediments. This in turn can impact benthic animals that are important prey to marine mammals, such as walrus, gray whales, and bearded seals.[77,78,79] A switch from benthic (lower) to pelagic (upper) marine ecosystem activities that link organisms and their environment, in combination with warmer temperatures, may result in this northern shelf region changing from a benthic-dominated to a pelagic-dominated marine ecosystem (Figure 26.4) and becoming a hotspot of invasion, expansion, and increased abundance of fish species such as pollock and Pacific salmon.[79] The changing conditions confer physiological and competitive benefits to species favoring warmer water conditions, such as saffron cod, and potential negative impacts to Arctic cod populations, a keystone species in Chukchi and Beaufort Seas food webs.[17]

Changes in climate-related events are likely to affect management actions and economic drivers, including fisheries, in complex ways.[80] An example is the recent heat wave in the Gulf of Alaska, which led to an inability of the fishery to harvest the Pacific cod quota in 2016 and 2017 and to an approximately 80% reduction in the allowable quota in 2018.[81] These reductions are having significant impacts on Alaska fishing communities and led the governor of Alaska to ask the Federal Government to declare a fisheries disaster. Events such as these are requiring the use of multiple, alternative models to appropriately characterize uncertainty in future population trends and fishery harvests.[82] The need to address uncertainty is especially true for the Eastern Bering Sea pollock fishery, which is one of the largest in the United States.[83] While most scientists agree that walleye pollock populations in the eastern Bering Sea are likely to decrease in a warming

climate,[84,85,86,87,88] these effects can be mitigated to some extent by adopting alternative fish harvest strategies,[89] and economic losses may be partially offset by increased pollock prices.[90]

Key Message 2

Terrestrial Processes

Alaska residents, communities, and their infrastructure continue to be affected by permafrost thaw, coastal and river erosion, increasing wildfire, and glacier melt. These changes are expected to continue into the future with increasing temperatures, which would directly impact how and where many Alaskans will live.

As temperatures increase across the Alaska landscape, physical and biological changes are also occurring throughout Alaska's terrestrial ecosystems. Degradation of permafrost (soil at or below the freezing point of water [32°F] for two or more years) is expected to continue, with associated impacts to infrastructure,[91] river and stream discharge,[92] water quality,[93,94] and fish and wildlife habitat. Wildfires and temperature increases have caused changes in forest types from coniferous to deciduous in interior Alaska, and these changes are projected to continue with increased future warming and fire.[95,96] In tundra ecosystems, temperature increases have allowed an increase of shrub-dominated lands.[97,98] With the late-summer sea ice edge located farther north than it used to be, storms produce larger waves and cause more coastal erosion.[19] In addition, ice that does form is very thin and easily broken up, giving waves more access to the coastline.[99] A significant increase in the number of coastal erosion events has been observed as the protective sea ice embankment is no longer present during the fall months.[100] In addition, glaciers continue to diminish, and associated runoff influences other terrestrial ecosystems.[101]

Permafrost

About half of Alaska is underlain by permafrost—an essential geographic quality that affects landscape patterns and processes,[102] and construction in the Arctic depends on the ability of permafrost to remain frozen. Since the 1970s, Arctic and boreal regions in Alaska have experienced rapid rates of warming and thawing of permafrost,[103,104,105,106] with spatial modeling[107] projecting that near-surface permafrost will likely disappear on 16% to 24% of the landscape by the end of the 21st century.[108] Confidence in these estimates is higher than for those in the Third National Climate Assessment[109] due to more field sample sites, higher resolution imagery for mapping, and advanced geographic modeling techniques.

Permafrost degradation impacts society in both tangible and intangible ways. Physical impacts of thawing permafrost include unsafe food storage and preservation (Box 26.2), decreased bearing capacities of building and pipeline foundations, damage to road surfaces, deterioration of reservoirs and impoundments that rely on permafrost for wastewater containment, reduced operation of ice and snow roads in winter, and damage to linear infrastructure (such as roads and power lines) from landslides.[20] As permafrost thaws, the ground sinks (known as subsidence), causing damage to buildings, roads, and other infrastructure;[110,111,112] these impacts to structures and facilities are likely to increase in the future.[91] In addition to physical impacts, thawing permafrost has important societal impacts that cannot be quantified. The loss of cultural heritage for Alaska's Indigenous people includes the loss of archaeological sites, structures, and objects, as well as traditional cultural properties, which affects their ability to connect to their ancestors and their past.[113]

Box 26.2: Iñupiat Work to Preserve Food and Traditions on Alaska's North Slope

Local traditional foods are important for nutritional, spiritual, cultural, and social benefits. Many of these foods are sometimes stored in traditional underground ice cellars kept cold by the surrounding permafrost. With warming climate conditions, many of these ice cellars are beginning to thaw, increasing the risks for foodborne illness, food spoilage, and even injury from structural failure. The Iñupiat community of Nuiqsut, located on Alaska's North Slope, is among the communities using new technology to improve the storage environment in existing cellars. Find out more at https://toolkit.climate.gov/case-studies/i%C3%B1upiaq-work-preserve-food-and-traditions-alaskas-north-slope.

Wildfire

The annual area burned by wildfires in Alaska varies greatly year-to-year, but the frequency of big fire years (larger than 2 million acres) has been increasing—with three out of the top four fire years (in terms of acres burned) in Alaska occurring since the year 2000.[114] As a result, the vegetation of forested Interior Alaska now has less acreage of older spruce forest and more of post-fire early successional vegetation, birch, and aspen than it did prior to 1990.[95] This change favors shrub-adapted wildlife species such as moose but also destroys the slow-growing lichens and associated high-quality winter range that caribou prefer, though the effects of fire-driven habitat changes to caribou population dynamics are uncertain.[23] Some rural communities, however, have adapted to these vegetation changes by designing small-scale programs that enhance moose browsing (feeding on leaves, twigs, or tree branches) or developing biofuel infrastructure integrated with fire prevention tactics.[115,116] In addition to range expansion due to changes in wildfire, shrubs have been increasing in density and height in tundra environments due to increasing temperatures,[98] with shrub expansion in tundra ecosystems being observed across the North American Arctic.[117,118] Shrub-adapted wildlife species such as moose and snowshoe hares, and in some cases beaver, have followed the expansion of shrubs and are now common in parts of Arctic Alaska and Canada, where they were previously rare or absent.[24,119,120] The area burned by wildfires may increase further under a warming climate.[25] Projections of burned area for 2006–2100 are estimated at 98 million acres under a lower scenario (RCP4.5) and 120 million acres under a higher scenario (RCP8.5).

Coastal and River Erosion

Flooding and erosion of coastal and river areas affect over 87% of the Alaska Native communities,[121,122,123,124,125] with some coastal areas being threatened due to changes in sea ice and increased storm intensity as a result of climate change.[122,126] Offshore and landfast sea ice is forming later in the season, which allows coastal storm waves to build while leaving beaches unprotected from wave action.[99,126,127,128,129] Rates of erosion vary throughout the state, with the highest rates measured on the Arctic coastline at more than 59 feet per year (Figure 26.5).[19] For context, one study noted that rates of coastal erosion may have varied from location to location but could have been more than 100 feet per year at the Canning River between Camden Bay and Prudhoe Bay.[130] Other researchers have come up with different rates along the Alaska Arctic coast.[19] Longer sea ice-free seasons, higher ground temperatures, and relative sea level rise are expected to worsen flooding and accelerate erosion in many regions, leading to the loss of terrestrial habitat and cultural resources and requiring entire communities, such as Kivalina in northwestern Alaska (Ch. 1: Overview, Figure 1.18),[131] to relocate to safer terrain.[19,122,123]

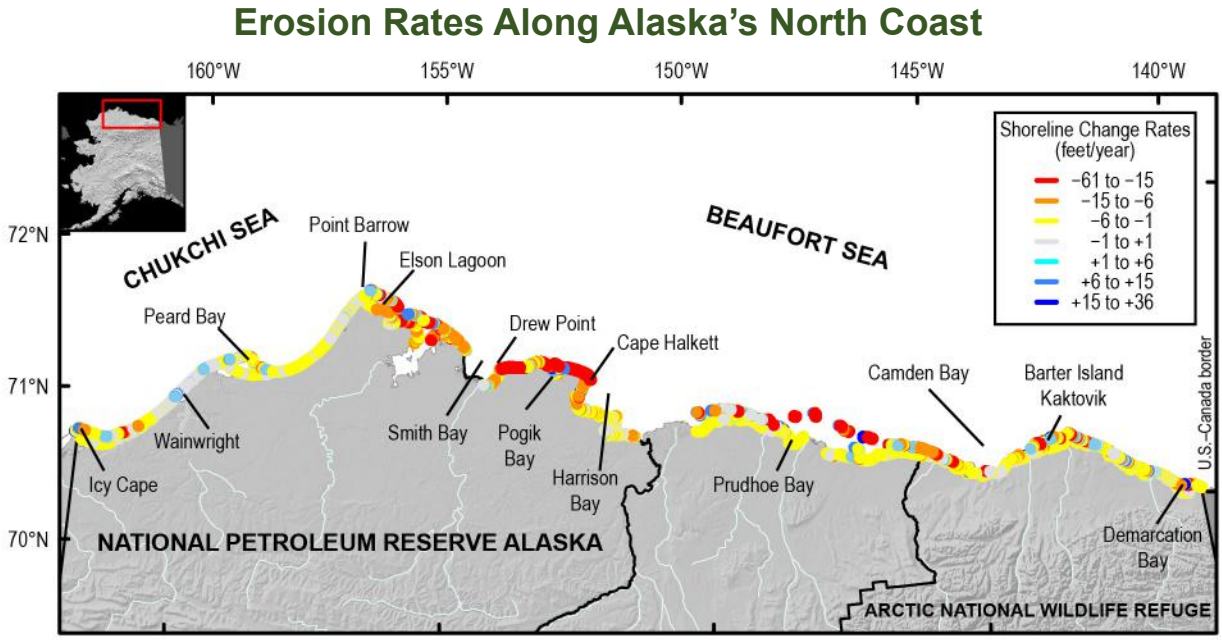


Figure 26.5: The map is of the north coast of Alaska and shows color-coded shoreline erosion rates, which can lead to the loss of habitat, cultural resources, and infrastructure. Source: adapted from Gibbs and Richmond 2015.[19]

Many Alaska communities that are not located on the coast are adjacent to large rivers, where riverine erosion is a serious problem,[123] with some communities (for example, Minto in 1969 and Eagle in 2009) having to relocate housing and other infrastructure due to erosion and associated flooding. Erosion rates vary, but conservative rates for the Ninglick River at Newtok range from 36 feet per year (west/downstream) to 83 feet per year (east/upstream), although actual observations by Newtok residents indicate a potential rate as high as 110 feet per year.[132] This has required the residents of Newtok to move to the new site of Mertarvik, about 9 miles away.[133]

In both coastal and river communities, various types of infrastructure and cultural resources are being threatened. A number of adaptation measures are being pursued or proposed[134,135] that include relocation, the construction of rock walls, the use of sandbags, and the placement of various forms of riprap, which may only slow or displace the erosion process and in some cases be maladaptive.[100,123]

Glacier Change

Glaciers continue to melt in Alaska, with an estimated loss of 75 ± 11 gigatons (Gt) of ice volume per year from 1994 to 2013,[136,137] 70% of which is coming from land-terminating glaciers; this rate is nearly double the 1962–2006 rate.[138] Several new modeling studies suggest that the measured rates of Alaska ice loss are likely to increase in coming decades,[139,140,141,142] with the potential to alter streamflow along the Gulf of Alaska[143] and to change Gulf of Alaska nearshore food webs.[144]

Melting glaciers are likely to produce uncertainties for hydrologic power generation,[22] which is an important resource in Alaska.[145,146] In the short term, melting glaciers can increase hydropower capacity by increasing downstream flow; however, with continued melting there will likely be less meltwater for the future. This may be offset by an increase in precipitation in Alaska,[45] although an increase in precipitation does not necessarily lead to increases in catchment runoff (Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM 5).[147]

Key Message 3

Human Health

A warming climate brings a wide range of human health threats to Alaskans, including increased injuries, smoke inhalation, damage to vital water and sanitation systems, decreased food and water security, and new infectious diseases. The threats are greatest for rural residents, especially those who face increased risk of storm damage and flooding, loss of vital food sources, disrupted traditional practices, or relocation. Implementing adaptation strategies would reduce the physical, social, and psychological harm likely to occur under a warming climate.

The influence of climate change on human health in Alaska can be traced to three sources: direct exposures, indirect effects, and social or psychological disruption. Each of these will have different manifestations for Alaskans when compared to residents elsewhere in the United States.

Direct Exposures

In general, even with a warming climate, Alaska is not expected to experience the extremes of heat and humidity found at lower latitudes; however, rising temperatures do pose a risk. Air conditioning in homes is rare in Alaska, so relief is seldom available for at-risk persons to escape high temperatures or from smoke exposure due to wildfires, assuming proper filters are not installed.

Winter travel has long been a key feature of subsistence food gathering activities for rural Alaska communities. Higher winter temperatures and shorter durations of ice seasons may delay or disrupt usual patterns of ice formation on rivers, lakes, and the ocean. For hunters and other travelers, this increases the risk of falling through the ice, having unplanned trip extensions, or attempting dangerous routes, leading to exposure injury, deaths, or drowning (Box 26.3).[26,148] Community search and rescue workers experience similar risks in searching for missing travelers, extending the threat across communities. Adaptation strategies being promoted include improved communication about local ice and water conditions, increasing use of survival suits and personal floatation devices,[149] and the use of personal locator beacons and messaging devices that can alert responders to a traveler at risk or provide reassurance and avoid unneeded search and rescue operations in high-risk conditions.[150]

Extreme weather events such as major storms, floods, and heavy rain events have all occurred in Alaska with resulting threats to human health.[153,154] For coastal areas, the damage from late-fall or winter storms is likely to be compounded by a lack of sea ice cover, high tides, and rising sea levels, which can increase structural damage to tank farms, homes, and buildings and can threaten loss of life from flooding. Such events can damage vital water and sanitation systems in several ways, including saltwater intrusion of drinking water sources, loss of power leading to freezing and damage to water and sewer systems, or disruptions to community septic drain fields and water distribution systems. These events would all reduce access to water/sewer services, leading to an increased risk of water-related infectious diseases.[155] Similar events threaten communities on rivers, where flooding due to increased glacial melt or heavy rains can cause extensive structural damage and loss of life. It is uncertain if climate warming will increase severe mid-winter ice jam events or reduce their hazards due to more gradual melting of ice with earlier spring thaws.[156] Improved real-time observations and river breakup forecasts are now available for use by decision-makers to help prepare in advance of

Box 26.3: Climate Change and Public Health

Environmental changes from a warming climate, such as unpredictable weather that greatly deviates from the norm, can significantly affect the physical and mental health of rural Alaskans. They may face difficulty harvesting local food and hazardous travel across the landscape. These climate-related challenges are being addressed by the Alaska Native Tribal Health Consortium Center for Climate and Health, which is working to recognize these new vulnerabilities and to support healthy adaptation strategies. Outcomes and activities from this effort include

- the One Health Group, which consists of federal, state, and nongovernmental organizations, conducts quarterly webinars and presentations on the intersection between human, animal, and environmental health. Cosponsored by the Centers for Disease Control and Prevention, this forum improves communication and situational awareness about climate change and public health in Alaska;[151]

- the Local Environmental Observer (LEO) Network,[6] a forum funded by the Environmental Protection Agency, the Department of the Interior, and the Bureau of Ocean Energy Management, is used for tracking local observations of environmental events and connecting communities with technical resources using an internet-based mapping tool and smartphone applications;

- comprehensive climate vulnerability assessments of rural Alaska communities;[152] and

- an electronic newsletter, *Northern Climate Observer*, which provides weekly access to articles and observations about the circumpolar north.[152]

More can be learned about these Alaska health-related resources at: https://toolkit.climate.gov/case-studies/addressing-links-between-climate-and-public-health-alaska-native-villages

potential flood events; such systems could help communities reduce the negative effects of seasonal flooding.[157]

Climate-driven increases in air pollution in Alaska are primarily linked to the increases in wildfire frequency and intensity. Wildfires, however, threaten individual safety in adjacent communities and pose risks downwind from smoke inhalation, particularly for children and persons with chronic respiratory and cardiovascular conditions (Ch. 13: Air Quality, KM 2; Ch. 14: Human Health, KM 1).[10,158] Adaptations to protect persons at risk from wildfire exposure include using community air quality indices linked to recommendations for specific groups, educating people about outdoor activities and use of masks, and creating a "clean room" using high-efficiency particulate air (HEPA) dust filters or air conditioning.[159] It is also likely that there will be an increased risk of respiratory allergies related to longer and more intense seasonal pollen blooms and mold counts (Ch. 13: Air Quality, KM 3).[160] Public reporting of pollen counts conducted in Anchorage and Fairbanks[161] is used to advise allergy sufferers of increasing risks and is linked to recommendations to avoid exposure and reduce symptoms. Increased respiratory symptoms have also been reported in communities that are experiencing

increased windblown dust. Adaptations include dust suppression, improving indoor air quality, and use of masks.

Indirect Effects

Climate change has indirect effects on human health in Alaska through changes to water, air, and soil and through ecosystem changes affecting the range and concentration of disease-spreading animals and food security, especially in rural communities (Ch. 14: Human Health, KM 1). These changes can result in positive and negative health effects; many are site specific, and documentation is highly dependent on availability of monitoring or reporting data.

In-home water and sanitation services are a fundamental contributor to health, and the absence of such services in 15% of rural Alaska homes is associated with increased risk of gastrointestinal, respiratory, and skin infections.[155,162,163] Climate-related environmental changes that can affect access to water and sanitation services have been well-documented.[154] These changes include loss of surface water through drainage of tundra ponds, lower source-water quality through increased riverbank erosion due to permafrost thaw or saltwater intrusion in coastal communities, and increased coastal erosion or storm surge leading to wastewater treatment system damage.[164] Permafrost thawing poses a threat to centralized water and wastewater distribution systems that need stable foundations to maintain system integrity. More flexible service connections have been used to reduce damage from movement caused by permafrost thawing.[165] People cope with water shortages by use of rainwater catchment or other untreated water sources, reuse of water used for clothes or personal hygiene, or rationing of water to prioritize drinking and cooking. Such practices, however, could lead to increased risk of waterborne infectious diseases or increased spread of person-to-person infections through decreased hygiene. Increased silt or organic material in source water can quickly clog filters, increasing costs of water treatment. This can result in reduced filtration effectiveness and increased exposure to waterborne pathogens, such as *Giardia intestinalis*.[165] The state of Alaska is funding development and testing of decentralized water and sanitation systems that use in-home treatment, water reuse, and other efficiencies that may be an alternative in homes without existing services or if centralized systems fail.[166]

Changes in insect and arthropod ranges due to climate change have raised human health concerns, such as the documented increase in venomous insect stings in Alaska.[167,168] Tick-borne human illnesses are uncommon in Alaska, but new reports of ticks on domestic dogs without travel exposure outside Alaska raise concerns about tick range extension into Alaska and the potential for introduction of new pathogens.[169] Several human infectious diseases could potentially expand in a changing Alaska climate. For example, climate change may allow some parasites to survive longer periods, provide an increase in the annual reproduction cycles of some disease-carrying insects and pests (vectors), or allow infected host animal species to survive winters in larger numbers, all increasing the opportunity for transmission of infection to humans.[170] However, some of these diseases are rare, and detecting increases is hampered by Alaska's small population, limited access to diagnostic testing, and the absence of surveillance for some human illness (for example, toxoplasmosis, an infection caused by a parasite). Foodborne pathogens, including parasites, have been identified as likely to increase due to increased temperature changes and increasing exposure.[171,172] In Alaska, disruption of ice cellars from thawing permafrost and coastal erosion has raised concerns about food spoilage or

infectious outbreaks, but documented human illness events are lacking. Likewise, the documented northward range expansion of beavers has been postulated to increase the threat of waterborne *Giardia* infections in humans; however, human *Giardia* illness reports have been stable in Alaska and show no increasing regional trends.[173] Emerging infectious threats led to the formation of an Alaska One Health Group, which meets quarterly to combine perspectives from human, animal, and environmental health and uses new data generated from the Local Environmental Observer (LEO) Network.[6,174] A new rural monitoring program has been developed for tribal community settings to include collection of data on infectious threats from food, animals, and water.[175]

Harmful algal blooms (HABs) produce toxins that can harm wildlife and pose a health risk to humans through consumption of contaminated shellfish. Because phytoplankton growth is increased in part by higher water temperatures, risks for HAB-related illnesses, including paralytic shellfish poisoning (PSP), may increase with climate change. PSP is a long-recognized, untreatable, and potentially fatal illness caused by a potent neurotoxin in shellfish. PSP illnesses are considered a public health emergency. Two approaches are being used to reduce PSP in Alaska. First, because recreational shellfish harvesting is very popular in Alaska (see Ch. 24: Northwest, KM 2 and 4 and Figure 24.7), some communities have begun to monitor for PSP toxins among shellfish at locations used for noncommercial harvests using a "catch, hold, and test" approach, which, if coupled with reliable testing methods, could provide a strategy to reduce risk and maintain these important local harvests.[176] The second adaptation approach uses local water temperature data to predict the risk of HAB growth in Kachemak Bay. The effectiveness of these methods for reducing human health risk has not been established.[7]

An example of climate-associated disease emergence and response is the 2004 outbreak of acute gastroenteritis that was associated with consumption of raw farmed oysters contaminated by the bacterium *Vibrio parahaemolyticus*. This is a well-recognized threat in warmer coastal waters of North America but was previously unreported in Alaska. However, in 2004, surface water temperatures above shellfish beds had warmed enough to support *V. parahaemolyticus* growth. This warming was part of a documented long-term warming trend, and the outbreak is indicative of a northward range extension of this pathogen by about 600 miles.[177] In response to the outbreak, the State of Alaska developed a control plan that includes water temperature monitoring around commercial oyster beds and uses threshold-based responses to reduce health risks from this pathogen.[176] Fortunately, *V. parahaemolyticus* contamination has not become a major health threat. Alaska has averaged only three reported cases per year since the first outbreak, and many of these are traceable to non-Alaska shellfish; however, the projected rise in sea surface temperatures in Alaska will favor increased *Vibrio* growth and seasonal range expansion with an increased risk of human exposure and illness.[178,179]

Psychological and Social Effects

Climate change is a common concern among Alaskans and is associated with feelings of depression and uncertainty about the potential changes to communities, subsistence foods, culture, and traditional knowledge and the potential of relocation from long-established traditional sites.[122] These uncertainties and threats have effects on mental health and on family and community relationships and may lead to unhealthy responses such as substance abuse and self-harm.[180] This is especially true of Indigenous peoples, who have a deep connection to their home areas, often described as sense of place.[181,182,183,184] Over generations,

Indigenous communities have developed extensive knowledge about their areas and the plants and animals with which they share an ecosystem.[185] As the effects of climate change are felt in the landscape, many Alaska Natives feel a sense of personal loss as the familiar has become unpredictable and sometimes strange.[125] This uncertainty has also reduced traditional camping activities that strengthen community ties. Damage or loss to cultural sites and properties is also a great concern, reducing the sense of cultural continuity in one's place along with information about living and adapting there. In the context of many other social, technological, economic, and cultural changes affecting Indigenous communities, the continuation of traditional activities in traditional places can be a bedrock of stability. When this, too, is threatened, a wider sense of environmental security is at risk.[125] Community relocation or the movement of persons away from climate-threatened areas can have intergenerational effects through loss of cultural connections and adverse childhood experiences leading to poorer health outcomes. The Alaskans most vulnerable to these climate-related changes are those who are most dependent on subsistence foods, the poor, the very young, the elderly, and those with existing health conditions that require ongoing care, that limit mobility, or that reduce capacity to accommodate changes in diet, family support, or stress.[11]

Key Message 4

Indigenous Peoples

The subsistence activities, culture, health, and infrastructure of Alaska's Indigenous peoples and communities are subject to a variety of impacts, many of which are expected to increase in the future. Flexible, community-driven adaptation strategies would lessen these impacts by ensuring that climate risks are considered in the full context of the existing sociocultural systems.

Alaska's climate is changing rapidly, with far-reaching effects throughout the state, including in its Indigenous communities. Alaska's rural communities are predominantly inhabited by Indigenous peoples, with some of them disproportionately vulnerable to socio-economic and environmental change; however, they also have rich cultural traditions of resilience and adaptation.[109,125,134,186,187,188] The impacts of climate change are likely to affect all aspects of Alaska Native societies, from nutrition, infrastructure (see Key Message 2), economics, and health consequences to language, education, and the communities themselves. Most of these impacts are also experienced in other rural, predominantly nonnative communities in Alaska and are therefore covered in other sections of this chapter.

Subsistence Activities

Subsistence hunting, fishing, and gathering provide hundreds of pounds of food per person per year in many Alaska Native villages.[189,190] Producing, preparing, sharing, and consuming these foods provide a wealth of nutritional, spiritual, cultural, social, and economic benefits. Traditional foods are widely shared within and between communities and are a way of strengthening social ties.[191,192,193] Climate change is altering the physical setting in which

these subsistence activities are conducted.[15,182] Examples include

- reducing the presence of shore-fast ice used as a platform to hunt seals[194] or butcher whales,[195]
- reducing the availability of suitable ice conditions for hunting seals and walrus (Figure 26.6),[28] and
- exacerbating the risks of winter travel due to increasing areas of thin ice and large fractures within the sea ice (commonly referred to as "leads") as well as water on rivers.[26,27,196]

However, climate change is also providing more opportunity to hunt from boats late in the fall season or earlier in spring.[125] Increasing temperatures affect animal distribution and can alter the availability of subsistence resources, often making hunting and fishing harder but sometimes providing new opportunities, such as fall whaling on St. Lawrence Island.[197] Shellfish populations, an important subsistence and commercial resource along the Alaska coast, have been declining for more than 20 years throughout coastal Alaska, with ocean warming and ocean acidification (Ch. 9: Oceans) contributing to the decline (see Key Message 1). Warm temperatures and increased humidity are also affecting ice cellars used traditionally to store food (as noted earlier in this chapter), thereby making it harder to air-dry meat and fish on outdoor racks, causing food contamination.[131,198] Some communities have found new storage methods or have changed to an increasingly Western diet. Subsistence foods decrease the costs of feeding a family compared to purchased foods, which in rural Alaska are almost twice the cost of those in Anchorage.[199,200] One net result of all these changes is an overall decrease in food security for residents of rural Alaska Native communities (Ch. 10: Ag & Rural, KM 4).[29]

Thawing permafrost in the boreal forest has accelerated land and riverbank erosion (see Key Message 2). Subsistence harvesters have expressed concern that less precipitation is resulting in rivers becoming shallower and lakes drying.[15] The increasingly dynamic nature of interior river characteristics has contributed to more challenging boat navigability and less dependable locations for fish wheel and net sets. These climate-induced environmental changes also occur in the context of other regulatory, social, administrative, legal, and economic constraints, which affect the ways that climate change impacts manifest themselves in specific locations.[201] As the environment changes, overall well-being can

Variable Weather Affects Harvest Levels

Figure 26.6: These images of marine mammal meat drying on racks in Gambell, Alaska, in (a) June 2012 and (b) July 2013 illustrate the interannual variability of harvests due to sea ice and weather conditions and suggest what the future may hold if ice and weather trends continue. Photo credit: Henry P. Huntington.

also suffer from the sense of dislocation and from losing the spiritual and cultural benefits of providing and sharing traditional foods, as these activities do much to tie communities together.[202,203,204]

Adaptation Actions

In the midst of negative impacts from climate change, Alaska Native communities display remarkable capacity for response and adaptation (Ch. 15: Tribes, KM 3).[29,125,205] Sometimes, adaptation means expanding networks for sharing of foods and ideas, as has been seen in the Kuskokwim River area;[206] applying Indigenous evidence and approaches to habitat protection;[27] or giving communities more say in identifying priorities for action and directing available funds for community needs and action-oriented science.[125] A clear example is the community of Shaktoolik's initiative to build a community-driven, mile-long and seven-foot-high berm made out of driftwood and gravel to protect itself from flooding and erosion during storm episodes.[207] As storms increase in frequency and intensity,[126] some builders in Gambell, Alaska, are considering efficient house designs that avoid exposure to prevailing winds and piling up of snow at the doors.[208,209] While some of these initiatives are part of statewide efforts to address common threats from climate change,[210] at other times communities have been able to take advantage of new opportunities, such as expanding networks for sharing of foods and ideas,[206] fishing for new species,[211] or applying Indigenous knowledge and frameworks to habitat protection and ecosystem management.[27] Further effort is warranted both on cataloging community response to climate-related changes in the environment and on enhancing the transfer of knowledge among rural communities on innovative and effective adaptations.[212]

Key Message 5

Economic Costs

Climate warming is causing damage to infrastructure that will be costly to repair or replace, especially in remote Alaska. It is also reducing heating costs throughout the state. These effects are very likely to grow with continued warming. Timely repair and maintenance of infrastructure can reduce the damages and avoid some of these added costs.

Climate change in Alaska has caused regionally disparate economic effects. The infrastructure and community relocation costs, along with potential adverse effects on fisheries, accrue predominantly to rural communities. While both urban and rural communities benefit from reduced space heating costs, the urban communities bear few of the costs and risks. The profound and diverse climate-driven changes in Alaska's physical environment and ecosystems generate economic impacts through their effects on environmental services. These services include positive benefits directly from ecosystems (for example, food, water, and other resources), as well as services provided directly from the physical environment (for example, temperature moderation, stable ground for supporting infrastructure, and smooth surface for overland transportation).[213] Some of these effects are relatively assured and in some cases are already occurring. Other impacts are highly uncertain, due to their dependence on the structure of global and regional economies and future human alterations to the environment[112] decades into the future, but they could be large.

Infrastructure

Threats to infrastructure in Alaska from coastal and riparian erosion caused by the combination of rising sea levels, thawing permafrost,

reduced sea ice, and fall storms are well known.[214,215] A study published in 2008 projected that the cost (for 2008–2030) associated with early reconstruction and replacement of public infrastructure (roads, public buildings, airports, and rail lines) caused by damage from these threats was estimated to be between $3.6 and $6.1 billion (in 2008 dollars).[20] Assuming the 2.85% annual real interest rate used in these studies, the cost translates to an average of $250 to $420 million per year (in 2015 dollars). A more recent study estimated a somewhat smaller annual cost of $110–$270 million between 2015 and 2060 for maintenance and repair costs to mitigate or remediate damage to public infrastructure from climate warming (in 2015 dollars, discounted 3%) under the lower scenario (RCP4.5) and higher scenario (RCP8.5), respectively.[11,91] Projecting these costs to the end of the century, cumulative effects amounted to $3.7 billion under the lower scenario (RCP4.5) to $4.5 billion under the higher scenario (RCP8.5) for reactive repair and replacement, but $2.0 to $2.5 billion for proactive adaptation costs, depending on the climate change scenario[11] (in 2015 dollars, discounted 3%). The lower cost assumes that funding will be available for maintenance and repair before facilities require replacement, which is not guaranteed.[216,217] Both studies excluded losses to commercial and industrial buildings and private homes.

Coastal and riverine erosion and flooding in some cases will require that entire communities, or portions of communities, relocate to safer terrain. The U.S. Army Corps of Engineers identified erosion threats to 31 communities requiring partial or complete relocation.[123] Relocation costs for seven vulnerable communities identified in a 2009 U.S. Government Accountability Office study ranged from $80 to $200 million per community (dollar year not reported).[122,218] Beyond financial cost, additional challenges of relocation involve legal and policy obstacles, as well as deep cultural ties to landscape and place. Construction of rock walls, use of sandbags and riprap,[219] and replacement infrastructure for communities that are partially relocated[123] represent additional costs, as would loss of productivity and income from lack of access to utilities and drinking water and temporary displacement of residents when water and sewer lines rupture.[220,221,222]

Ice Road Transportation

In rural Alaska, where surface transportation infrastructure is extremely limited, snow and ice offer a low-cost alternative for moving people, goods, and heavy industrial equipment. As the climate warms, the resulting shorter and milder cold season reduces the season length for ice road use, increases the risk of travel on river ice, and increases the wear and tear on snow machines. Loss of overland winter transportation raises costs for extractive industries (such as oil extraction and logging) and rural Alaska households. A 2004 report estimated the cost of ice roads on the North Slope of Alaska at $100,000 per mile, versus as much as $2 million per mile for a gravel road (in 2003 dollars; $127,000 per mile for ice roads and $2.5 million for gravel in 2015 dollars).[223] Costs of foregone economic activity[103] and increased risk of winter travel are more difficult to quantify.[224]

Marine Vessel Traffic

Reduced seasonal ice has been associated with increased marine traffic in the U.S. maritime Arctic.[225] A longer ice-free shipping season could reduce the cost of shipping ore from the Red Dog mine and other mines in the region,[154,226] as well as increase certainty of shipping production facilities and equipment to North Slope oil fields. Adverse navigability effects of reduced river discharge[227] could offset beneficial effects of an extended ice-free shipping season on the cost of barge service to communities in western and northern Alaska.

Northward progression of the late-summer sea ice edge creates opportunities for increased vessel traffic of various types (including cargo and tanker ships, tour boats, and government vessels, including military)[226] to pass through the Bering Strait to or from the Northern Sea Route, the Northwest Passage,[228] and, by mid-century, directly across the Arctic Ocean.[229,230] As the Arctic Ocean opens, the Bering Strait will have increased strategic importance.[231] Lack of deep-water ports, vessel services, search and rescue operations, environmental response capabilities, and icebreaking capacity will impede expansion of vessel traffic.[225,226,230,232,233] Significant effects are likely several decades away, and new transarctic shipping will likely have little economic effects within Alaska in the near term but would bring environmental risks to fisheries and subsistence resources.[234] New oil and gas exploration and development in new areas within the U.S. economic zone are unlikely, as the Arctic Ocean waters that are not already accessible are generally off the U.S. continental shelf.

Wildfire Costs

Increasing incidence of wildfire near inhabited areas leads to a wide array of costs, including firefighting costs, health and safety impacts, property damage, insurance losses, and higher costs of fire insurance (Figure 26.7).[235] In addition, tourism businesses may experience short-term losses as visitors avoid recently burned areas. A recent estimate projected an increase in wildfire suppression costs of $25 million more per year (in 2015 dollars, 3% discount rate) under the lower scenario (RCP4.5) above the 2002–2013 annual average by the end of the century.[21] The cost could be higher if the footprint of human settlement expands and the geographic area designated for active fire suppression expands accordingly. Property damage from wildfires will likely increase as the number of large fire years increases. The Millers Reach Fire in 1996 destroyed 454 structures, including 200 homes in the Matanuska-Susitna Borough, with an estimated total cost of $80 million (in 1996 dollars; $120 million in 2015 dollars).[236] A subsequent fire in 2015 in the same general area destroyed another 55 homes and heavily damaged 44 other structures.[237]

Wildfire Destroys Homes Near Willow, Alaska

Figure 26.7: The 7,220-acre Sockeye Fire near Willow, Alaska, totally destroyed 55 residences and damaged 44 in mid-June 2015. Photo courtesy of Matanuska-Susitna Borough/Stefan Hinman.

Heating Costs

Increasing winter temperatures have reduced the demand for energy and associated costs to provide space heating for Alaska homes, businesses, and governments. Heating degree days (a measure of the energy required to heat homes and other buildings) have declined substantially in most parts of the state as compared to mid-20th century levels, including 5% in Sitka, 6% in Fairbanks and Nome, and up to 8% in Anchorage and Utqiaġvik (formerly known as Barrow; Figure 26.8).[238]

Energy Needed for Heating Decreases Across Much of Alaska

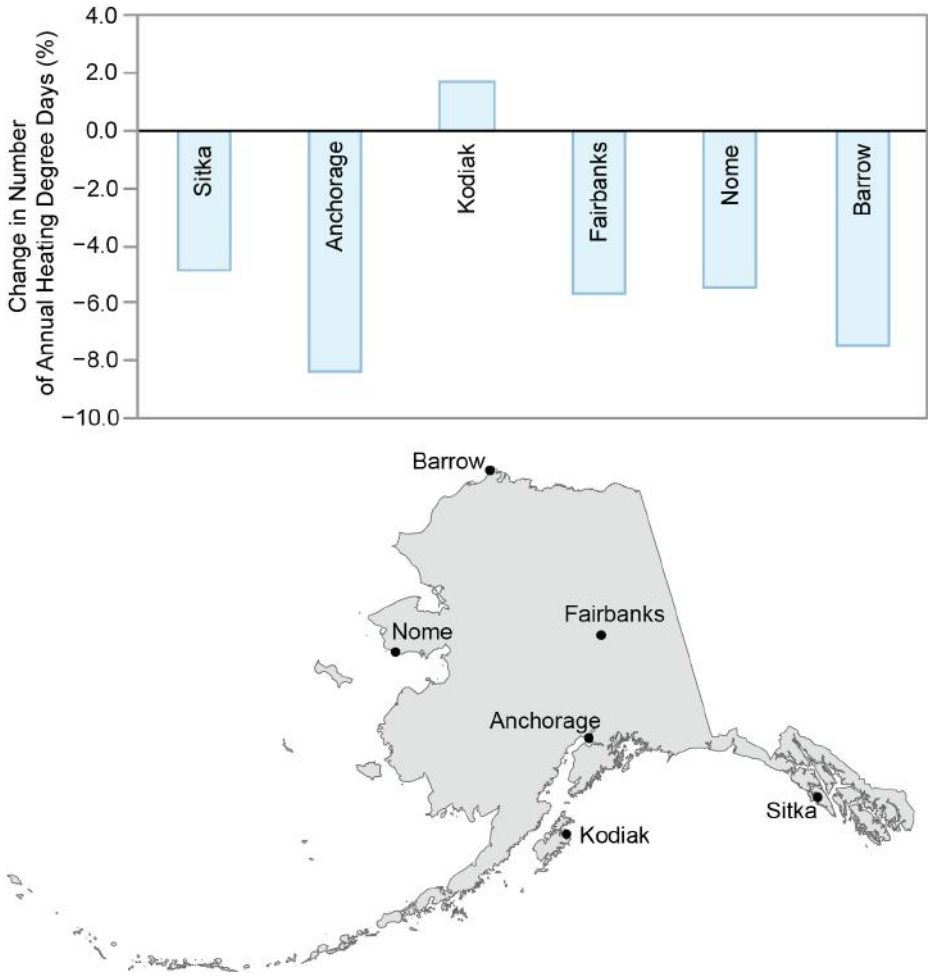


Figure 26.8: The chart shows the percentage change in annual heating degree days for the period 2000–2015 (as compared to 1950–1979) for six Alaska communities. Every 1% decline in heating degree days could potentially yield $10 million of annual savings in heating costs. Sources: University of Alaska Anchorage, NOAA NCEI, and ERT Inc.

Unlike in other regions of the United States, increased cooling degree days (a measure of the energy required to cool homes and other buildings) from warmer summer temperatures provide only a small offset to the beneficial effect of lower heating costs. Applying 2017 retail fuel prices to data on energy use for space heating for Alaska regions, annual expenditures for space heating in Alaska are estimated at about $1 billion (in 2015 dollars).[239,240] Future energy prices are highly uncertain, but the figures suggest that every 1% decline in heating degree days could yield $10 million of annual savings in heating costs.

Key Message 6

Adaptation

Proactive adaptation in Alaska would reduce both short- and long-term costs associated with climate change, generate social and economic opportunity, and improve livelihood security. Direct engagement and partnership with communities is a vital element of adaptation in Alaska.

Alaska and its adjacent Arctic areas are experiencing some of the largest climate changes in the United States (Ch. 2: Climate, KM 7).[14] As such, residents, governments, and

industry must prepare for and adapt to the changing climate and associated environmental changes if the most severe impacts are to be avoided.[187,188,241]

Adaptation is often defined as an adjustment in human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects[242] and is an iterative, ongoing process that involves assessment and redirection as needed (Ch. 28: Adaptation).[243] Efforts to prepare for and adapt to the impacts of climate change in Alaska can reduce costs associated with the impacts of climate change,[20,91] generate social and economic opportunities,[244,245] and improve livelihood security.[125,246,247,248] Vulnerability analyses of Alaska communities indicate adaptation as a key element to address high vulnerabilities to biophysical impacts of climate change [249] and ocean acidification.[250]

Key elements of successful adaptation in Alaska include coordinated consideration of both environmental and social conditions[134] and careful attention to local context; there is no "one-size-fits-all" strategy.[187,188,251] Enhanced communication, coordination, knowledge sharing, and collaboration are important components of adaptation in Alaska. This includes between communities, among scientists and communities, and across government bodies at the tribal, community, borough, state, and national levels.[251,252,253,254,255,256,257] Building adaptation solutions in partnership with local knowledge is vital for ensuring that adaptations meet local needs and priorities.[254,258,259,260,261]

A range of adaptations to changing climate and related environmental conditions are underway in Alaska, and others have been proposed as potential actions.[135] These adaptations involve human health and poverty alleviation,[136,188] livelihood security,[125] ecosystem management,[262] new construction designs for housing,[263] and a host of other options.[135] Some of these measures reduce vulnerability and risk, while others involve more systemic institutional transformation.[255,260]

At the federal level, there are several key motivations for Arctic Strategies created by various U.S. Government agencies, including 1) recognizing the need to adapt to a changing climate, 2) identifying critical research gaps, 3) creating a vision for regional resilience, and 4) acknowledging the need to safeguard national security under changing environmental conditions.[264,265,266]

Climate change action plans and vulnerability assessments have been completed by several municipalities in Alaska.[135] Formal tribal adaptation planning and preliminary planning activities such as workshops, trainings, webinars, monitoring, and vulnerability assessments have been conducted throughout the state. As of this writing, three climate adaptation plans have been completed and three additional projects are underway to produce climate adaptation plans (Figure 26.9).[8] The Bureau of Indian Affairs awarded eight Climate Resilience Program Awards for adaptation planning between 2013 and 2019.[8] Research has identified 31 adaptation planning-related trainings (2012–2017) and 43 meetings, workshops, and summits (1998–2017).[8] The state-funded Alaska Climate Change Impact Mitigation Program provides funding for hazard mitigation planning, including climate-related hazards such as flooding, coastal erosion, and permafrost thaw.[8,135]

Adaptation Planning in Alaska

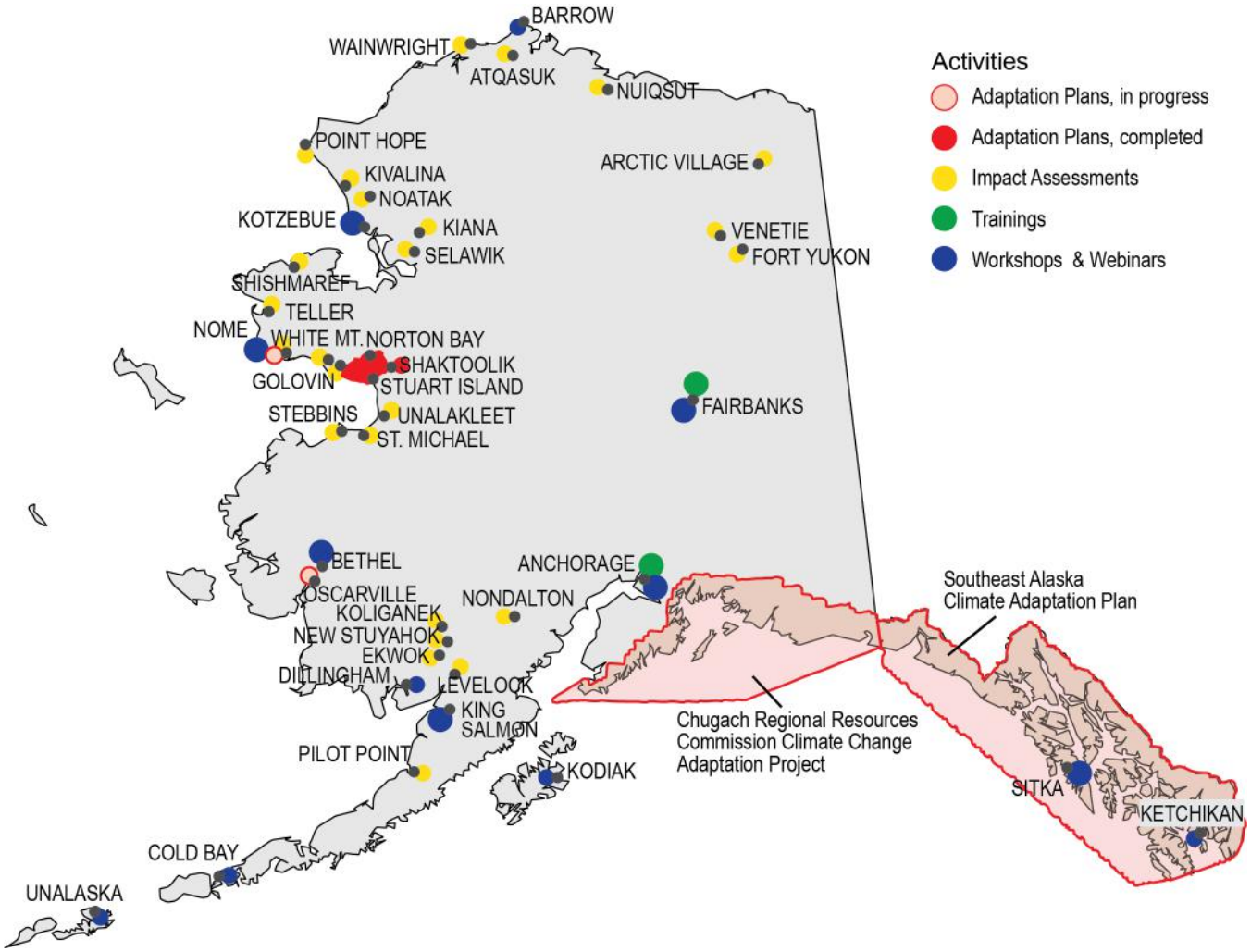


Figure 26.9: The map shows tribal climate adaptation planning efforts in Alaska. Research is considered to be adaptation under some classification schemes.[1,2] Alaska is scientifically data poor, compared to other Arctic regions.[3] In addition to research conducted at universities and by federal scientists, local community observer programs exist through several organizations, including the National Weather Service for weather and river ice observations;[4] the University of Alaska for invasive species;[5] and the Alaska Native Tribal Health Consortium for local observations of environmental change.[6] Additional examples of community-based monitoring can be found through the website of the Alaska Ocean Observing System.[7] Source: adapted from Meeker and Kettle 2017.[8]

In contrast to planning and research, action in response to climate change involves active implementation of plans, changes in policy, protocol, or standard operating procedures, as well as direct reaction to hazards.[135] In the wildfire management and response sector in Alaska, adaptations include establishment of new suppression crew training, evolution of tools used to suppress fire, change in the statutory start date of fire season, and the implementation of community wildfire protection plans.[135]

Several communities in Alaska face immediate threats from climate-related environmental changes, the most severe of which is erosion and coastal inundation related to permafrost thaw and lack of sea ice during fall and winter storms.[122,267] Short-term disaster risk management, such as shoreline revetment, is thus part of adaptation in Alaska.[242] Longer-term planning and village relocation efforts are also underway in two villages but face significant hurdles.[268,269]

Creating decision support tools, establishing climate services and knowledge networks, and providing data sharing and social media have been proposed as additional methods for adapting to the effects of climate change in Alaska.[219,270,271,272,273] Tools that can identify and evaluate policy options under a range of scenarios of future conditions are particularly beneficial in the Arctic, including Alaska.[274,275]

Examples of decision support tools in the state include the Historical Sea Ice Atlas and the SNAP (Scenarios Network for Alaska + Arctic Planning) climate-outlook community charts[276] of projected temperature and precipitation for each community in Alaska. Periodically evaluating decision support tools helps to ensure their usefulness to stakeholders in practical decision contexts.[277]

The use of technology can facilitate the creation and expansion of knowledge networks through events such as webinars[278,279] and social media, such as the newly established AdaptAlaska.org portal and the Local Environmental Observer (LEO) Network that connects people through information, both locally and internationally.[6] Data sharing can be accomplished with online tools such as portals and data hubs; however, the isolated nature of remote, rural communities in Alaska constrains internet connectivity. In addition, technological solutions alone are insufficient to fully meet the information needs of rural communities in the region.[253,271]

A range of climate adaptation guidebooks exist that focus on climate adaptation planning in Alaska and neighboring Canada, which faces related adaptation challenges.[134] These guidebooks have been created by universities, governments, and nongovernmental organizations for a range of audiences, including rural Native Alaska communities, local governments, and state governments. Consistent across the majority of the guidebooks are key phases in the adaptation planning process that include building partnerships and networks of stakeholders; conducting vulnerability and risk assessments; establishing priorities, options, and an implementation plan and evaluation metrics; implementing the preferred option; and conducting ongoing monitoring and adjustment of activities (Ch. 28: Adaptation).[134]

Acknowledgments

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Traceable Accounts

Process Description

The Alaska regional chapter was developed through public input via workshops and teleconferences and review of relevant literature, primarily post 2012. Formal and informal technical discussions and narrative development were conducted by the chapter lead and contributing authors via email exchanges, teleconferences, webinars, in-person meetings, and public meetings. The authors considered inputs and comments submitted by the public, the National Academies of Sciences, Engineering, and Medicine, and federal agencies. The author team also engaged in targeted consultations during multiple exchanges with contributing authors, who provided additional expertise on subsets of the Traceable Account associated with each Key Message.

Key Message 1

Marine Ecosystems

Alaska's marine fish and wildlife habitats, species distributions, and food webs, all of which are important to Alaska's residents, are increasingly affected by retreating and thinning arctic summer sea ice, increasing temperatures, and ocean acidification. Continued warming will accelerate related ecosystem alterations in ways that are difficult to predict, making adaptation more challenging (*very likely, very high confidence*).

Description of evidence base

Changes in arctic sea ice and its impacts on marine ecosystems and various biological resources are well documented by 38 years of satellite records[280] and the scientific literature.[48,50,51,77,78,79,281] The finding of a continuing retreat of arctic sea ice is supported by sea ice modeling and continued CO_2 emissions.[37,46] The northward distribution of ocean fish species is documented by numerous scientific papers: see Perry et al. (2005),[282] Thorsteinson and Love (2016),[17] and Mecklenburg et al (2002).[72] The impacts of an increased open Arctic sea contributing to increases in ocean acidification[18] and expanding deeper into the Arctic Basin[57] will need validation with further studies.

Major uncertainties

To date, relatively few of Alaska's marine species have been studied for their response to ocean acidification, and the assessment of potential impacts is challenging due to each species' differing habitats, life cycle stages, and response and adaptation mechanisms. It is known that some organisms respond more dramatically to environmental change than others, and warming ocean temperatures may be more significant in the short term than ocean acidification. There is significant uncertainty in the projected increase of shipping through the Arctic and the Bering Strait, since much of this increase will be driven by economic factors and not climate or other environmental change.

Description of confidence and likelihood

There is *very high confidence* that the arctic sea ice will continue to reduce in size over the next 20–40 years, and it is *likely* that the Arctic Ocean will be nearly ice-free in late summer by mid-century based on current climate models. There is also *high confidence* that this melting will

have an effect on the northward expansion of North Pacific fish species and associated effects on associated food webs. There is *very high confidence* that continued melting of the Arctic Ocean ice will have an effect on the habitat and behavior of polar bear and walrus. There is *high confidence* that Alaska's ocean waters are becoming increasingly acidic. Given this increase, it is *very likely* that there will be biological impacts, but it is uncertain which species will be affected and to what extent.

Key Message 2

Terrestrial Processes

Alaska residents, communities, and their infrastructure continue to be affected by permafrost thaw, coastal and river erosion, increasing wildfire, and glacier melt. These changes are expected to continue into the future with increasing temperatures, which would directly impact how and where many Alaskans will live (*very likely, high confidence*).

Description of evidence base

Permafrost

Multiple studies of permafrost in Alaska have shown that the gradual warming of the ground[105] has resulted in the warming and thawing of permafrost over the past 30 years,[79,104,106] and spatial modeling projects that near-surface permafrost will potentially disappear on up to a quarter of the landscape by the end of the 21st century.[108] The magnitude of these changes depends on climate and ground-ice conditions, where permafrost thaw generally results in drier upland habitat and wetter lowlands as tundra and forests are converted to lakes and bogs.[106,283] These changes will undoubtedly result in a number of societal consequences, loss of wildlife habitat, damage to infrastructure (including buildings, airport runways, tank farms, and roads), ecosystem contamination, and increased maintenance costs.[20,21,91,207,284,285]

Wildfire

It has been well documented that wildfires are a common occurrence in Alaska, especially the interior boreal areas, although they have also occurred in areas of arctic tundra,[114,286] with some of the largest fire years (1–6 million acres) occurring between 2004 to 2016 since records began around 1950.[114] Recent studies show that changes in wildfire across the Alaska landscape could be attributed to human activity.[287] This has resulted in changes in boreal vegetation cover[95,96] and tundra communities.[286] The increased fire frequency of recent decades is expected to continue into the future, in spite of the change to less flammable deciduous vegetation, because of the accompanying change to warmer and drier conditions.[95] The ground is warmer under post-fire deciduous vegetation, and thus fires will enhance the thaw of permafrost that is already underway due to climatic warming.[288]

Coastal and River Erosion

The shoreline along Alaska's northern coast has eroded at some of the fastest rates in the Nation, putting local communities, oil fields, and coastal habitat at risk.[19] Unlike the contiguous United States, Alaska is subject to glacial and periglacial processes that make permafrost and sea ice key controlling factors of coastal erosion and flooding. Thermal degradation of permafrost leads to

enhanced rates of erosion along permafrost-rich coastal shorelines[19] and subsidence of already low-lying regions. Longer sea ice-free seasons, higher ground temperatures, and relative sea level rise are expected to exacerbate flooding and accelerate erosion in many regions, leading to the loss of more shoreline in the future.[19]

While erosion and changed river courses are a normal part of landscape evolution, lateral river erosion rates are likely to change over time, but the direction and magnitude of these changes are poorly understood. Major river erosion events are typically tied to high hydrological flows or the melting of permafrost along river and stream banks. Statewide, evidence for changes in maximum gauged streamflows is mixed, with a majority of locations having no significant trend.[289] There is significance for seasonal changes in the timing of peak flows in interior Alaska, though increases in the absolute magnitude are not well evident in existing data.[290] Riverine erosion is a serious problem for a significant number of communities.[123] Significant resources have been expended to slow erosion at some communities, often through the construction of berms and bank stabilization projects. These projects have a mixed record of success and nearly always require ongoing maintenance.

Glacier Change

Airborne altimetry surveys of Alaska glaciers spanning the 1994–2013 interval and covering about 40% of the region's glacierized area[137] yield decadal timescale mass balance estimates for individual glaciers and a regional estimate.[291] Several new modeling studies suggest that the measured rates of Alaska ice loss are likely to increase in coming decades,[139,140,141,142] with substantial regional-scale reductions in glacier area, volume (up to 40%–60% loss), and number. Moreover, physically based runoff models suggest that runoff from glaciers accounts for almost 40% of the total freshwater discharge into the Gulf of Alaska.[292]

Interdisciplinary research along the Gulf of Alaska is providing new insights into the role of glacier runoff in structuring downstream freshwater and nearshore marine ecosystems.[101] End-of-century projections from physically based models suggest that anticipated atmospheric warming (2°–4.5°C) will drive volume losses of 32%–58% for Alaska glaciers.[142] Increases in river chemical ions due to glacial runoff and permafrost melt have also been associated with diminishing glaciers in Alaska.[94,291]

Major uncertainties

Some events such as wildfires and coastal storms are dependent on regional and local current weather conditions, and the exact landscape or ecosystem response can be highly variable. Future effects are also dependent on quick response actions and adaptation measures.

Description of confidence and likelihood

There is *high confidence* that wildfire in Alaska will continue but *medium confidence* as to its ultimate effect on vegetation and permafrost, which is often dependent on fire fields available (e.g., older forests or new growth shrublands), the fire intensity, and the return rate. There is *high confidence* that the north coast of Alaska is eroding at high rates. It is *likely* that coastal erosion is accelerating in response to climate change but *medium to low confidence* as to the location and rate because of limited studies and datasets documenting this. There is *high confidence* that river erosion will continue but *medium confidence* as to when, where, and to what extent this will occur

across Alaska because of differences in local climatic and geographic qualities of the area in question. There is *high confidence* and it is *likely* that the glaciers in Alaska will continue to diminish, especially those that are tidewater glaciers.

Key Message 3

Human Health

A warming climate brings a wide range of human health threats to Alaskans, including increased injuries, smoke inhalation, damage to vital water and sanitation systems, decreased food and water security, and new infectious diseases (*very likely, high confidence*). The threats are greatest for rural residents, especially those who face increased risk of storm damage and flooding, loss of vital food sources, disrupted traditional practices, or relocation. Implementing adaptation strategies would reduce the physical, social, and psychological harm likely to occur under a warming climate (*very likely, high confidence*).

Description of evidence base

The evidence base for climate-related health threats can be divided into three main categories. First are those threats that have strong documentation of both the climate or environmental driver and the health effect. An example is the emergence of gastrointestinal illness due to the northward expansion of the bacteria *Vibrio parahaemolyticus* among Alaska shellfish. Other threats with a similar level of evidence include increased venomous insect stings.

Second, some health threats are based on a combination of well-documented climate-driven environmental changes and records of anecdotal community observations of health impacts. Examples include the increased risk of injury or death from exposure among winter subsistence-related travelers or respiratory problems from smoke inhalation during wildfires. The community observations of these threats point to a real trend.[10,158] However, there is no historical or current means to document and track such injuries or exposures. Therefore, objective evidence, such as increased rates of occurrence or peer-reviewed reports, is not currently available. Other threats that fit this category include respiratory symptoms from dust and pollen, decreased food security, and loss of cultural and traditional lifestyles and practices along with the accompanying mental health or social disruption effects.

The third category is those threats that are logical inferences of potential health risks based on documented environmental changes and community-vulnerability assessments. Examples include the well-documented threats from coastal storms to community infrastructure and shorelines and the damage to community water and sanitation systems from permafrost thawing or erosion. The risk of physical harm from major storm or flooding events is obvious, and the loss of a water/sewer system would likewise pose a clear threat to health through waterborne or water-washed infections. However, these threats are based on likely outcomes from existing trends in environmental change. The human health effects are either undocumented or are anticipated in the future. Many of the infectious disease risks and harmful algal blooms (HABs) fall into this category; where range expansion of pathogens or vectors is occurring, health effects are likely to follow.

Major uncertainties

The greatest uncertainties in the health threats of climate change lie in the geographic distribution, magnitude, duration, and capacity to detect the effects. Many of the impacts of climate changes are most evident in rural Alaska, which is an enormous area and sparsely populated. Thus, sporadic events with geographic variability such as storms or HABs may have a range of human health effects from none to severe, depending on the timing and location of exposure. Likewise, the magnitude and duration of the effects on health are difficult to predict based on variability in the source of risk and human adaptation. The lack of repeated outbreaks of *V. parahaemolyticus* illnesses from raw shellfish consumption is a good example of how adaptations in aquaculture practices and commercial regulations, along with likely changes in consumer practices, appear to have reduced the magnitude of the health threats, compared with initial outbreak. Finally, we have limited capacity to detect many of the health outcomes associated with climate change. The organized reporting and monitoring of climate-linked health effects by public health are limited to the toxin-mediated illnesses, some of the infectious diseases, mortality events, and unusual clusters of illnesses or injuries. Even among those conditions, underreporting of illnesses is common due to healthcare-seeking behavior, lack of recognition by medical providers due to unfamiliarity or limited diagnostic capacities, or incomplete compliance. For many of the anticipated health effects, such as nonoccupational injuries, mental health issues, and respiratory conditions, there may be documentation in a person's individual health records, but no systems are in place to collect such information and link these illnesses to climate or environmental events or conditions. Large administrative healthcare databases, such as the Alaska Hospital Discharge Data System or the Alaska Health Information Exchange, could be used for focused investigations or ongoing monitoring. However, these would only be useful for severe illnesses with large geographic or multiyear distributions. These datasets would likely miss health events that do not result in emergency room visits or hospitalizations, that are rare, or that occur in irregular episodes. Data from ambulatory clinic visits, community surveys, or syndrome-based surveillance efforts would be needed to detect and characterize uncommon or less severe health occurrences.

Description of confidence and likelihood

There is *high confidence* that there will be a continuation of trends causing higher winter temperatures, increased storm events, increased frequency and extent of wildfires, and increased permafrost thawing with associated erosion. Given these trends, there is *very likely* to be subsequent human health effects, but the distribution and magnitude of these effects remain uncertain.

Key Message 4

Indigenous Peoples

The subsistence activities, culture, health, and infrastructure of Alaska's Indigenous peoples and communities are subject to a variety of impacts, many of which are expected to increase in the future (*likely, high confidence*). Flexible, community-driven adaptation strategies would lessen these impacts by ensuring that climate risks are considered in the full context of the existing sociocultural systems (*likely, medium confidence*).

Description of evidence base

Many studies have examined different aspects of Alaska's Indigenous communities, including the ways climate change is affecting or can affect subsistence,[15,26,28,29,30,125,131,194,197,198,293] culture,[125,182,184] health,[27,29,294] and infrastructure.[20,21,164,295] Alaska's Indigenous peoples are increasingly involved in the research efforts, not just as informants or assistants but as those shaping and asking research questions and as those analyzing and interpreting the results of studies.[27,29,125,190] As a result, research on the impacts of climate change on Alaska's Indigenous peoples is increasingly focused on topics of direct relevance to daily lives and long-term/historical interests and is increasingly attentive to the context in which those changes occur. In other words, there is increasing confidence that the right questions are being asked and the answers are being interpreted in the right way.[29,125]

Major uncertainties

There is little question that climate change is having widespread and far-reaching impacts on Alaska's Indigenous peoples. It is less clear, however, exactly which peoples and communities are responding to the changes they face. One community may be able to seize a new opportunity or may be able to adjust effectively to at least some forms of change, whereas another community will not be able to do either. More needs to be understood about these differences, the reasons for them, and how adaptability and resilience can be fostered.

It is also unclear how, exactly, the changes will influence one another as they occur in the context of all that is happening in Alaska Native life. For example, climate change may mean hunters have to travel farther to hunt. GPS allows for more reliable navigation, and four-stroke engines provide more confidence when traveling farther offshore. At the same time, rising fuel prices mean it is more expensive to travel far, perhaps limiting the ability of a hunter to take advantage of better navigation and motors. How these competing influences will balance out is difficult to say and requires more attention.

Description of confidence and likelihood

There is *high confidence* that climate change is having far-reaching effects on Alaska's Indigenous peoples. It is *likely* that most of these impacts will have negative effects, as they undermine existing behaviors, patterns, infrastructure, and expectations. It is also *likely* that there will continue to be some benefits and opportunities stemming from climate-related changes. There is *medium confidence* that the negative impacts can be reduced and the new opportunities maximized with appropriate policy and regulatory action, as not all aspects of change can be addressed in this way, and it is unclear whether such a systematic approach is plausible in light of the way programs and policies are administered in Alaska's Indigenous communities.

Key Message 5

Economic Costs

Climate warming is causing damage to infrastructure that will be costly to repair or replace, especially in remote Alaska (*very likely, high confidence*). It is also reducing heating costs throughout the state (*likely, medium confidence*). These effects are very likely to grow with continued warming (*very likely, high confidence*). Timely repair and maintenance of infrastructure can reduce the damages and avoid some of these added costs (*likely, high confidence*).

Description of evidence base

Coastal erosion affects a number of coastal communities, with the highest rates on the Arctic coastline.[19] Coastal erosion and flooding in some cases will require that entire communities, or portions of communities, relocate to safer terrain. The U.S. Army Corps of Engineers identified erosion threats to 31 communities requiring partial or complete relocation.[123] Relocation costs for seven vulnerable communities identified in a 2009 U.S. Government Accountability Office (GAO) study ranged from $80 to $200 million per community.[122]

Melting glaciers will increase the role of seasonal precipitation patterns for hydroelectric power generation. River discharge has been increasing during the winter since the 1960s, but because reservoirs are generally full in fall, investments to increase reservoir heights would be required to take advantage of increased fall precipitation.[145]

National Weather Service (NWS) daily weather summaries show that heating degree days have already declined by 5% in Sitka, 6% in Fairbanks and Nome, and 8% in Anchorage and Utqiaġvik (formally known as Barrow) as compared to mid-20th century levels. The same NWS data show that increased cooling degree days from warmer summer temperatures provide only a small offset to the beneficial effect of lower heating costs.

Major uncertainties

The extent, rate, and patterns of coastal erosion at locations other than along the north coast, and including deltas and rivers, are poorly known. Change in the patterns and trends of erosion (for example, an increase in the rate associated with warming and climate change), is expected but poorly documented for most locations due to the scarcity of historical data.

Future energy prices are highly uncertain, generating a high level of uncertainty around the dollar value of the savings in space heating costs associated with the projected decline in heating degree days.

Wildfire suppression costs depend on future policy decisions for wildfire management. Property damage from wildfire depends on uncertain future settlement and development patterns.

Description of confidence and likelihood

There is *high confidence* and it is very likely that future damage to infrastructure from thawing permafrost and coastal erosion will cost hundreds of millions of dollars annually to repair or replace. There is *high confidence* and it is *likely* that timely repair and maintenance of

infrastructure can reduce damages and avoid some of the added costs. There is *medium confidence* and it is *very likely* that these costs will be offset in part by savings from reduced space heating needs.

Key Message 6

Adaptation

Proactive adaptation in Alaska would reduce both short- and long-term costs associated with climate change, generate social and economic opportunity, and improve livelihood security (*likely, high confidence*). Direct engagement and partnership with communities is a vital element of adaptation in Alaska (*likely, very high confidence*).

Description of evidence base

Research investigating costs of adapting to projected climate changes in Alaska in the realms of public infrastructure and wildfire suppression indicates cost savings from adaptation.[21,91] Rural Alaska communities have high reliance on subsistence food resources. Access to these resources, as well as their habitat and migration patterns, is impacted by several factors, including climate change. Adaptation is thus important for maintaining livelihood security in these communities.[125,246,247,248] Vulnerability analyses of Alaska communities indicate adaptation as a key element to address high vulnerabilities to biophysical impacts of climate change[249] and ocean acidification.[250] Rural communities in Alaska share many climatic, cultural, and ecosystem properties with rural communities across the Arctic. Research in Canada has documented the social and economic opportunities from adaptation in Northern communities.[244,245]

Adaptation actions to the impacts of climate change in Alaska have been transitioning from awareness and concern to education and actions.[135,251] There are a number of documents that describe climate change related research needs and actions associated with infrastructure, economics, hazards and safety, and terrestrial ecosystem impacts, as well as other concerns of rural Alaska Native communities.[8,135,252,271] Adaptation actions that address these same needs have also been described in Canada and the circumpolar Arctic.[135] The importance of direct engagement and partnership with communities in adaptation is emphasized throughout the literature.[125,187,205,252,253,254,258,259,260,261,271,296,297]

Most research reports on case studies and actions that describe transparent, collaborative, and accessible information though data sharing, building of networks, and long-term partnerships with communities.[252,253,254,260,261] Climate change has also been described as a risk management problem, with proposed actions that address risk and inform risk management actions being offered.[255]

A number of climate adaptation guidebooks focus on Alaska and Canada, which have related adaptation challenges.[134] Universities, governments, and nongovernmental organizations produced these guidebooks for a range of audiences, including rural Alaska Native communities, local governments, and state governments. Key phases in the adaptation planning process that are consistent across the majority of the guidebooks include building partnerships and networks of stakeholders; conducting vulnerability and risk assessments; establishing priorities, options, and

an implementation plan and evaluation metrics; implementing the preferred option; and conducting ongoing monitoring and adjustment of activities.[134] Guidebooks specific to Alaska Natives and Canadian Inuit and First Nations peoples emphasize the importance of community support and participation in the adaptation planning process.[134]

Major uncertainties

Little research has been conducted to track and evaluate the efficacy of implementation of existing adaptation planning in Alaska or to assess the possibilities for maladaptation. Similarly, the feedbacks and synergies are not well documented between adaptation and changes in physical, natural, and social systems. More research is needed to understand cross-sector and cumulative impacts and how they can best be addressed in an all-inclusive manner.[135]

Description of confidence and likelihood

There is *high confidence* that proactive adaptation can reduce costs, generate social and economic opportunity, and improve livelihood security. It is *likely* and there is *high confidence* that proactive adaptation will be affected by external factors, such as global markets that are beyond the control of the organization or institution implementing the adaptations.

It is *likely* and there is *very high confidence* that direct engagement and partnership with communities will be a critical element of adaptation success, as this has strong evidence and high consensus in the literature; however, there are a limited number of publications that document this partnership model in Alaska.

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27 Hawai‘i and U.S.-Affiliated Pacific Islands

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27 Hawai‘i and U.S.-Affiliated Pacific Islands

Honolulu, Hawai‘i

Key Message 1

Threats to Water Supplies

Dependable and safe water supplies for Pacific island communities and ecosystems are threatened by rising temperatures, changing rainfall patterns, sea level rise, and increased risk of extreme drought and flooding. Islands are already experiencing saltwater contamination due to sea level rise, which is expected to catastrophically impact food and water security, especially on low-lying atolls. Resilience to future threats relies on active monitoring and management of watersheds and freshwater systems.

Key Message 2

Terrestrial Ecosystems, Ecosystem Services, and Biodiversity

Pacific island ecosystems are notable for the high percentage of species found only in the region, and their biodiversity is both an important cultural resource for island people and a source of economic revenue through tourism. Terrestrial habitats and the goods and services they provide are threatened by rising temperatures, changes in rainfall, increased storminess, and land-use change. These changes promote the spread of invasive species and reduce the ability of habitats to support protected species and sustain human communities. Some species are expected to become extinct and others to decline to the point of requiring protection and costly management.

Key Message 3

Coastal Communities and Systems

The majority of Pacific island communities are confined to a narrow band of land within a few feet of sea level. Sea level rise is now beginning to threaten critical assets such as ecosystems, cultural sites and practices, economies, housing and energy, transportation, and other forms of infrastructure. By 2100, increases of 1–4 feet in global sea level are very likely, with even higher levels than the global average in the U.S.-Affiliated Pacific Islands. This would threaten the food and freshwater supply of Pacific island populations and jeopardize their continued sustainability and resilience. As sea level rise is projected to accelerate strongly after mid-century, adaptation strategies that are implemented sooner can better prepare communities and infrastructure for the most severe impacts.

Key Message 4

Oceans and Marine Resources

Fisheries, coral reefs, and the livelihoods they support are threatened by higher ocean temperatures and ocean acidification. Widespread coral reef bleaching and mortality have been occurring more frequently, and by mid-century these events are projected to occur annually, especially if current trends in emissions continue. Bleaching and acidification will result in loss of reef structure, leading to lower fisheries yields and loss of coastal protection and habitat. Declines in oceanic fishery productivity of up to 15% and 50% of current levels are projected by mid-century and 2100, respectively, under the higher scenario (RCP8.5).

Key Message 5

Indigenous Communities and Knowledge

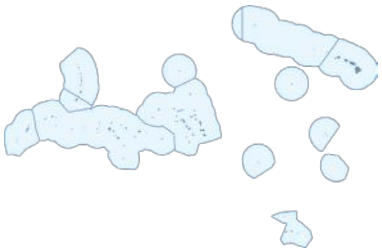
Indigenous peoples of the Pacific are threatened by rising sea levels, diminishing freshwater availability, and shifting ecosystem services. These changes imperil communities' health, well-being, and modern livelihoods, as well as their familial relationships with lands, territories, and resources. Built on observations of climatic changes over time, the transmission and protection of traditional knowledge and practices, especially via the central role played by Indigenous women, are intergenerational, place-based, localized, and vital for ongoing adaptation and survival.

Key Message 6

Cumulative Impacts and Adaptation

Climate change impacts in the Pacific Islands are expected to amplify existing risks and lead to compounding economic, environmental, social, and cultural costs. In some locations, climate change impacts on ecological and social systems are projected to result in severe disruptions to livelihoods that increase the risk of human conflict or compel the need for migration. Early interventions, already occurring in some places across the region, can prevent costly and lengthy rebuilding of communities and livelihoods and minimize displacement and relocation.

Executive Summary



The U.S. Pacific Islands are culturally and environmentally diverse, treasured by the 1.9 million people who call them home. Pacific islands are particularly vulnerable to climate change impacts due to their exposure and isolation, small size, low elevation (in the case of atolls), and concentration of infrastructure and economy along the coasts.

A prevalent cause of year-to-year changes in climate patterns around the globe[1] and in the Pacific Islands region[2] is the El Niño–Southern Oscillation (ENSO). The El Niño and La Niña phases of ENSO can dramatically affect precipitation, air and ocean temperature, sea surface height, storminess, wave size, and trade winds. It is unknown exactly how the timing and intensity of ENSO will continue to change in the coming decades, but recent climate model results suggest a doubling in frequency of both

El Niño and La Niña extremes in this century as compared to the 20th century under scenarios with more warming, including the higher scenario (RCP8.5).[3,4]

On islands, all natural sources of freshwater come from rainfall received within their limited land areas. Severe droughts are common, making water shortage one of the most important climate-related risks in the region.[5] As temperature continues to rise and cloud cover decreases in some areas, evaporation is expected to increase, causing both reduced water supply and higher water demand. Streamflow in Hawai'i has declined over approximately the past 100 years, consistent with observed decreases in rainfall.[6]

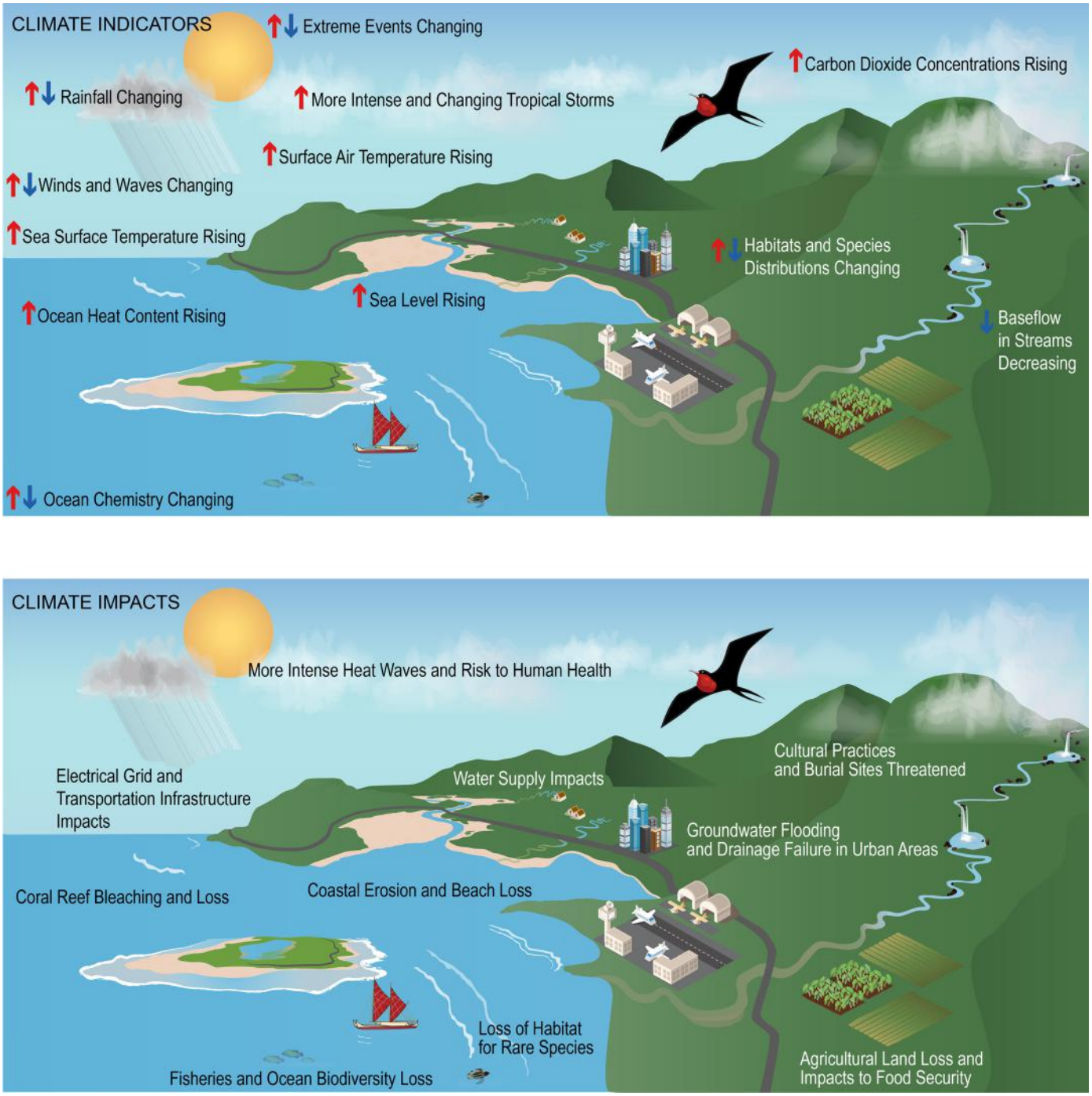
The impacts of sea level rise in the Pacific include coastal erosion,[7,8] episodic flooding,[9,10] permanent inundation,[11] heightened exposure to marine hazards,[12] and saltwater intrusion to surface water and groundwater systems.[13,14] Sea level rise will disproportionately affect the tropical Pacific[15] and potentially exceed the global average.[16,17]

Invasive species, landscape change, habitat alteration, and reduced resilience have resulted in extinctions and diminished ecosystem function. Inundation of atolls in the coming decades is projected to impact existing on-island ecosystems.[18] Wildlife that relies on coastal habitats will likely also be severely impacted. In Hawai'i, coral reefs contribute an estimated $477 million to the local economy every year.[19] Under projected warming of approximately 0.5°F per decade, all nearshore coral reefs in the Hawai'i and Pacific Islands region will experience annual bleaching before 2050. An ecosystem-based approach to international management of open ocean fisheries in the Pacific that incorporates climate-informed catch limits is expected to produce more realistic future harvest levels and enhance ecosystem resilience.[20]

Indigenous communities of the Pacific derive their sense of identity from the islands. Emerging issues for Indigenous communities of the Pacific include the resilience of marine-managed areas and climate-induced human migration from their traditional lands. The rich body of traditional knowledge is place-based and localized[21] and is useful in adaptation planning because it builds on intergenerational sharing of observations.[22] Documenting the kinds of governance structures or decision-making hierarchies created for management of these lands and waters is also important as a learning tool that can be shared with other island communities.

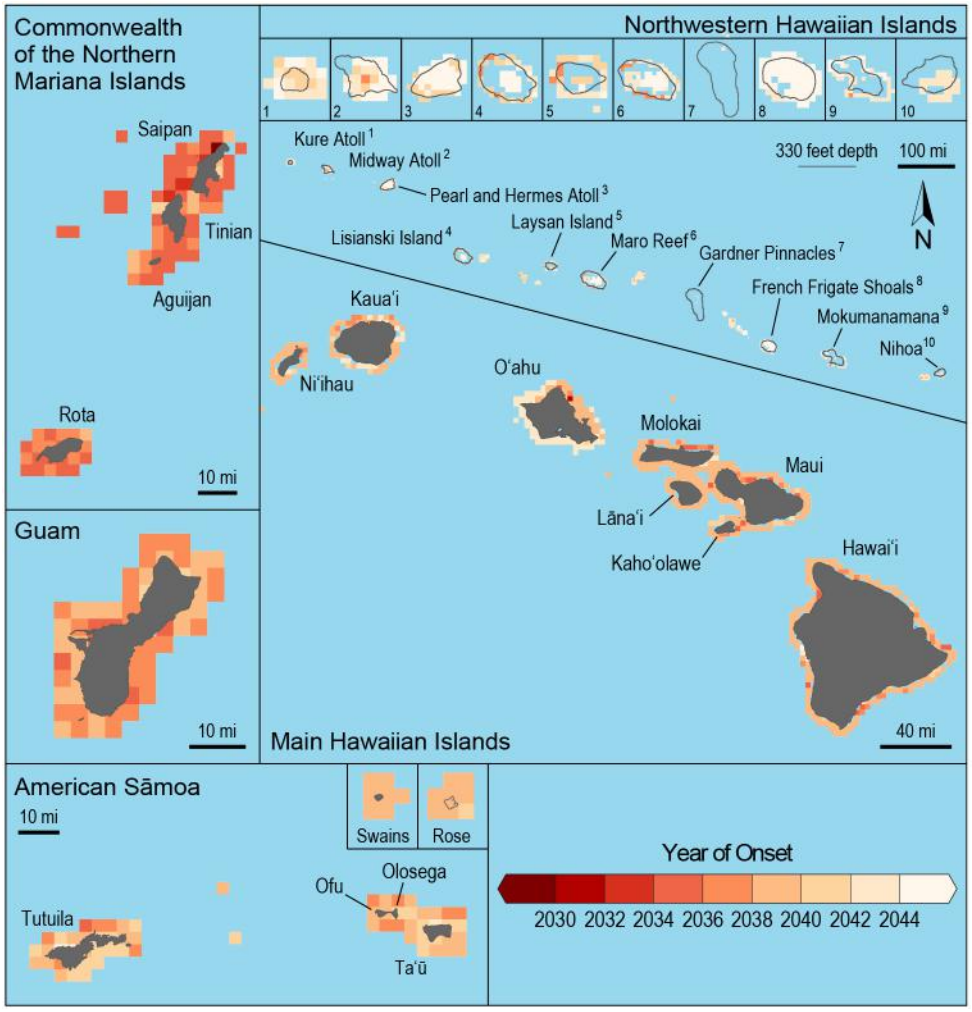
Across the region, groups are coming together to minimize damage and disruption from coastal flooding and inundation as well as other climate-related impacts. Social cohesion is already strong in many communities, making it possible to work together to take action. Early intervention can lower economic, environmental, social, and cultural costs and reduce or prevent conflict and displacement from ancestral land and resources.

Climate Indicators and Impacts



Monitoring regional indicator variables in the atmosphere, land, and ocean allows for tracking climate variability and change. (top) Observed changes in key climate indicators such as carbon dioxide concentration, sea surface temperatures, and species distributions in the U.S.-Affiliated Pacific Islands region result in (bottom) impacts to multiple sectors and communities, including built infrastructure, natural ecosystems, and human health. Connecting changes in climate indicators to how impacts are experienced is crucial in understanding and adapting to risks across different sectors. *From Figure 27.2 (Source: adapted from Keener et al. 2012)*.[23]

Projected Onset of Annual Severe Coral Reef Bleaching



The figure shows the years when severe coral reef bleaching is projected to occur annually in the Hawai'i and U.S.-Affiliated Pacific Islands region under a higher scenario (RCP8.5). Darker colors indicate earlier projected onset of coral bleaching. Under projected warming of approximately 0.5°F per decade, all nearshore coral reefs in the region will experience annual bleaching before 2050. From *Figure 27.10 (Source: NOAA)*.

Background

The U.S. Pacific Islands (Figure 27.1) are culturally and environmentally diverse, treasured by the 1.9 million people who call them home. The region comprises a vast ocean territory and more than 2,000 islands that vary in elevation, from high volcanic islands such as Mauna Kea on Hawai'i Island (13,796 feet) to much lower islands and atolls such as Majuro Atoll in the Republic of the Marshall Islands (the highest point on Majuro is estimated at 9 feet).[24,25,26] Its environments span the deepest point in the ocean (Mariana Trench National Monument) to the alpine summits of Hawai'i Island.[23] The region supports globally important marine and terrestrial biodiversity, as well as stunning cultural diversity (over 20 Indigenous languages are spoken).[23]

The U.S. Pacific Islands region is defined by its many contrasting qualities. While the area is a highly desirable tourist destination, with Hawai'i and the U.S.-Affiliated Pacific Islands (USAPI) drawing more than 10 million tourists in 2015,[27]

Pacific Islands Region Map

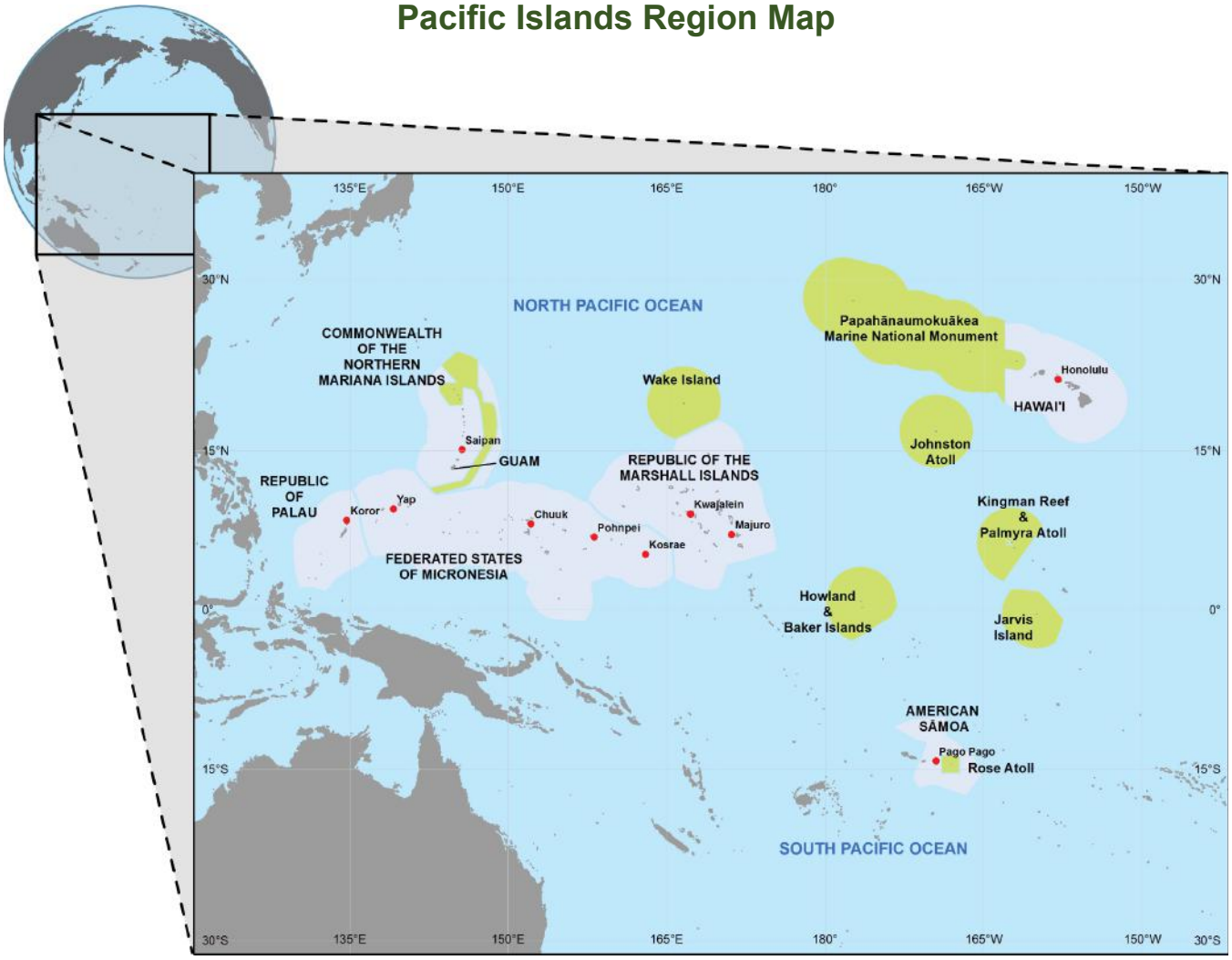


Figure 27.1: The U.S. Pacific Islands region includes the state of Hawai'i, as well as the U.S.-Affiliated Pacific Islands (USAPI): the Territories of Guam and American Sāmoa (AS), the Commonwealth of the Northern Mariana Islands (CNMI), the Republic of Palau (RP), the Federated States of Micronesia (FSM), and the Republic of the Marshall Islands (RMI). While citizens of Guam and the CNMI are U.S. citizens, those from AS are U.S. nationals. Under the Compact of Free Association (COFA), citizens from FSM, RP, and RMI can live and work in the United States without visas, and the U.S. armed forces are permitted to operate in COFA areas. On this map, shaded areas indicate the exclusive economic zone of each island, including regional marine national monuments (in green). Source: adapted from Keener et al. 2012.[23]

living in the islands carries climate-related risks, such as those from tropical cyclones, coastal flooding and erosion, and limited freshwater supplies. Because of the remote location and relative isolation of the islands, energy and food supplies are shipped in at high costs.

For example, Hawai'i has the highest average electricity rate in the United States (more than twice the national average),[28] and more than 85% of food is imported on most islands (see Ch. 17: Complex Systems and Ch. 20: U.S. Caribbean, Background and KM 5 for more information on the importance of regional supply chains).[29,30,31] Though the islands are small, they are seats for key military commands, with forces stationed and deployed throughout the region providing strategic defense capabilities to the United States.

Despite the costs and risks, Pacific Islanders have deep ties to the land, ocean, and natural resources, and they place a high value on the environmental, social, and physical benefits associated with living there. Residents engage in diverse livelihoods within the regional economy, such as tourism, fishing, agriculture, military jobs, and industry, and they also enjoy the pleasant climate and recreational opportunities. Important challenges for the region include improving food and water security, managing drought impacts, protecting coastal environments and relocating coastal infrastructure, assessing climate-induced human migration, and increasing coral reef resilience to warming and acidifying oceans.

New Research Validates and Expands on Previous Assessment Findings

In previous regional climate assessments, key findings focused on describing observed trends and projected changes in climate indicator variables for specific sectors.[23,32] In many cases, new observations and projections indicate that there is less time than previously thought for decision-makers to prepare for climate impacts.

Regionally, air and sea surface temperatures continue to increase, sea level continues to rise, the ocean is acidifying, and extremes such as drought and flooding continue to affect the islands.[33] New regional findings include (Figure 27.2)

- a limited set of detailed statistical and dynamical downscaled temperature, rainfall, and drought projections for Hawai'i (unlike the 48 contiguous states, Hawai'i—like the Alaska and U.S. Caribbean regions—does not have access to numerous downscaled climate projections; see Key Messages 1 and 6);[34,35,36]
- projected future changes to winds and waves due to climate change, which affect ecosystems, infrastructure, freshwater availability, and commerce (see Key Message 3);[37,38]
- more spatially refined and physically detailed estimates showing increased sea level rise for this century (see Key Messages 3 and 6);[17,39]
- models of how central Pacific tropical cyclone tracks are shifting north (see Key Message 3);[40]
- identification of urbanized areas vulnerable to flooding from rising groundwater and erosion (see Key Messages 1, 3, and 6);[8,41]
- detailed assessment of vulnerability to sea level rise in Hawai'i (see Key Message 3);[42]
- climate vulnerability assessments for endemic and endangered birds and plants showing shifting habitats (see Key Messages 2 and 5);[43,44] and
- projections that corals will bleach annually throughout the entire Pacific Islands region by 2045 if current warming continues (the worst bleaching event ever observed occurred during the El Niño of 2015–2016; Key Messages 4 and 6).[45,46,47,48]

Climate Indicators and Impacts

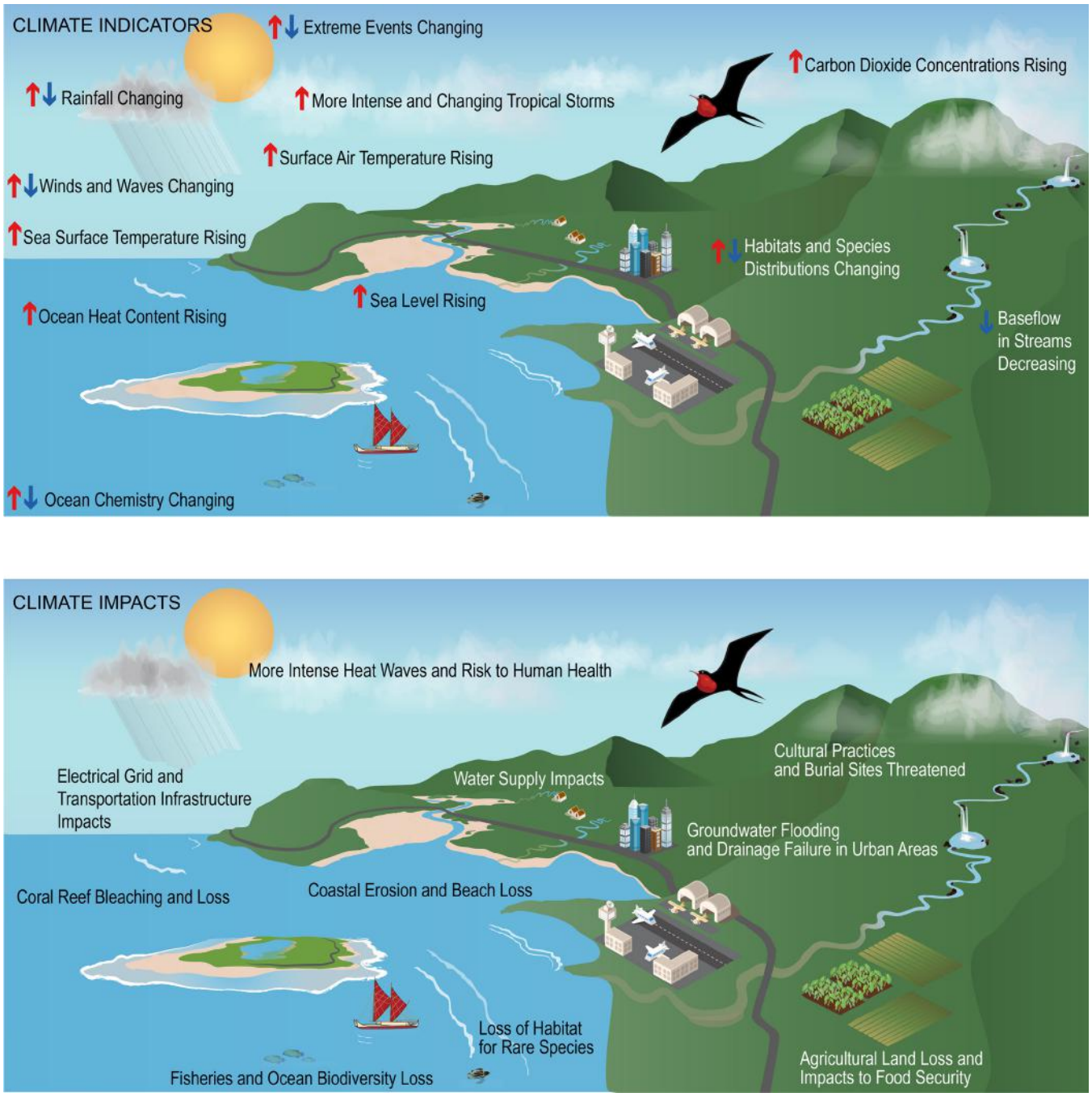


Figure 27.2: Monitoring regional indicator variables in the atmosphere, land, and ocean allows for tracking climate variability and change. (top) Observed changes in key climate indicators such as carbon dioxide concentration, sea surface temperatures, and species distributions in the Hawai‘i and U.S.-Affiliated Pacific Islands region result in (bottom) impacts to multiple sectors and communities, including built infrastructure, natural ecosystems, and human health. Connecting changes in climate indicators to how impacts are experienced is crucial in understanding and adapting to risks across different sectors. Source: adapted from Keener et al. 2012.[23]

Box 27.1: El Niño–Southern Oscillation (ENSO) and Year-to-Year Climate Variability

The El Niño–Southern Oscillation (ENSO) phenomenon is a prevalent cause of year-to-year changes in climate patterns globally[1] and in the Pacific Islands region.[2] The effects of ENSO can be magnified when it is in phase with longer periodic cycles such as the Pacific Decadal Oscillation and the Interdecadal Pacific Oscillation.[49] The El Niño and La Niña phases of ENSO can dramatically affect precipitation, air and ocean temperature, sea surface height, storminess, wave size, and trade winds (for details about the different patterns of global climate variability, see Perlwitz et al. 2017).[1]

Figure 27.3 shows how the typical seasonal patterns of rainfall, sea level, and storminess in El Niño and La Niña play out across the region, during which severe droughts can occur in the central and western Pacific and large areas of coral reefs can experience bleaching.[50,51] The strength of these ENSO-related patterns in the short term can make it difficult to detect the more gradual, long-term trends of climatic change. Understanding and anticipating ENSO effects, however, is important for planning for climate impacts on island communities and natural resources. Already, increases in the strength of El Niño and La Niña events have been observed (though the link between these observed changes and human causes is unclear).[3,52] It is unknown exactly how the timing and intensity of ENSO will continue to change in the coming decades, but recent climate model results suggest a doubling in frequency of both El Niño and La Niña extremes in the 21st century as compared to the 20th century under scenarios with more warming, including the higher scenario (RCP8.5).[3,4]

Seasonal Effects of El Niño and La Niña in the Pacific Islands Region

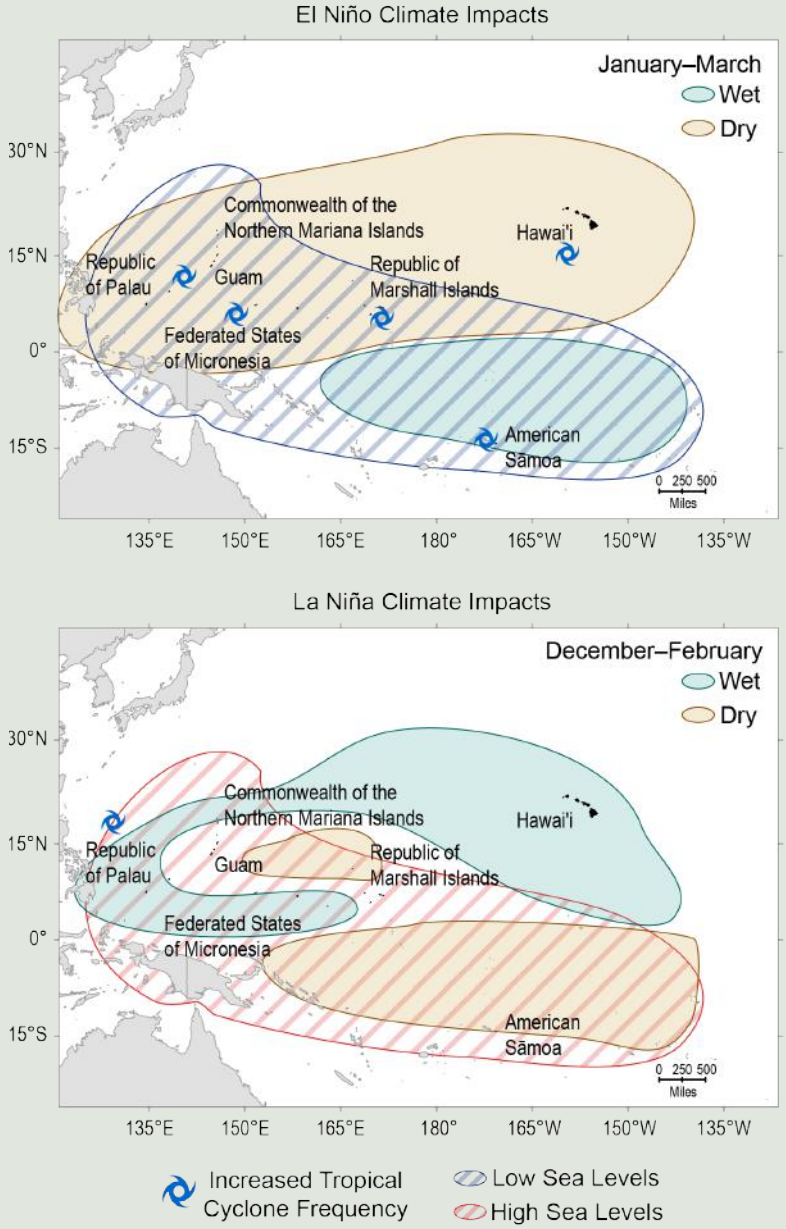


Figure 27.3: A prevalent cause of year-to-year changes in climate patterns in the U.S. Pacific Islands region is the El Niño–Southern Oscillation (ENSO) phenomenon. These maps show how (top) El Niño and (bottom) La Niña most commonly affect precipitation, sea level, and storm frequency in the Pacific Islands region in the year after an ENSO event. During certain months in the boreal (northern) winter, El Niño and La Niña commonly produce patterns that are different from those following an ENSO neutral year. After an El Niño, islands in the central Pacific (such as Hawai'i) and islands in the western Pacific (such as the Republic of Palau and Guam) experience drier than normal conditions from January to March, while the western and southern Pacific see abnormally low sea levels. After a La Niña, the patterns are reversed and occur earlier (December through February).[50] Source: East-West Center.

Risks and Adaptation Options Vary with Geography

In the U.S. Pacific Islands region, the severity of the impacts of climate change differ among communities. A number of factors affect both the level of risk and a community's approach to responding to that risk: geography (for example, high-elevation islands versus low-elevation atolls), the proximity of critical infrastructure to the coast, governance structure, cultural practices, and access to adaptation funding. As in the U.S. Caribbean (see Ch. 20: U.S. Caribbean), climate change is projected to impact the U.S. Pacific Islands through changes in ecosystem services, increased coastal hazards, and extreme events. Adaptation options in both regions are unique to their island context and more limited than in continental settings.

While uncertainty will always exist about future climate projections and impacts, communities and governments in the U.S. Pacific Islands region are planning proactively. Already, policy initiatives and adaptation programs are significant and include the accreditation of the Secretariat of the Pacific Regional Environment Programme (SPREP) to the Green Climate Fund,[53] the passage of the Hawai‘i Climate Adaptation Initiative Act,[54] and the creation of separate climate change commissions for the City and County of Honolulu (established 2018) and the State of Hawai‘i (established 2017). To increase coordination of adaptation and mitigation initiatives across the region and foster future climate leadership, island nations and the State of Hawai‘i signed the Majuro Declaration.[55] These initiatives are moving adaptation science forward, for example, by increasing freshwater supply, upgrading vulnerable infrastructure, and creating legal frameworks for state and local governments to build climate resilience into current and future plans and policies.

Key Message 1

Threats to Water Supplies

Dependable and safe water supplies for Pacific island communities and ecosystems are threatened by rising temperatures, changing rainfall patterns, sea level rise, and increased risk of extreme drought and flooding. Islands are already experiencing saltwater contamination due to sea level rise, which is expected to catastrophically impact food and water security, especially on low-lying atolls. Resilience to future threats relies on active monitoring and management of watersheds and freshwater systems.

On islands, all natural sources of freshwater come from rainfall received within their limited land areas. Piping water from neighboring states is not an option, making islands uniquely vulnerable to climate-driven variations and changes in rainfall, rates of evaporation, and water use by plants. The reliability of precipitation is a key determinant of ecosystem health, agricultural sustainability, and human habitability.

Severe droughts are common, making water shortage one of the most important climate-related risks in the region.[5] In water emergencies, some islands rely on temporary water desalination systems or have water sent by ship, both of which are costly but life-saving measures (Figure 27.4).[56] Droughts occur naturally in this region and are often associated with El Niño events. Rainfall in Hawai‘i and the U.S.-Affiliated Pacific Islands (USAPI) is strongly affected by seasonal movement of the intertropical convergence zone and ENSO (see Box 27.1). Similarly, other patterns of climate variability, such as the Pacific Decadal Oscillation, produce strings of wet or dry years lasting decades in the region. Because of this natural

Emergency Drought Response Action for Island Residents

Figure 27.4: U.S. Navy sailors unload reverse osmosis water supply systems in the Republic of the Marshall Islands in 2013 to provide relief from severe drought. The systems will produce potable water for more than 15,000 Ebeye Island residents. Photo credit: Mass Communication Specialist 2nd Class Tim D. Godbee, U.S. Navy.

variability, including dry seasons and frequent dry years, Pacific islands are highly vulnerable to any climate shifts that reduce rainfall and increase the duration and severity of droughts.

Compounding the direct effects of climate change, such as changing rainfall patterns, are the impacts of sea level rise on groundwater and groundwater-fed surface environments, such as wetlands and open lakes and ponds in low islands. For atoll islands, residents depend on shallow aquifers for some of their domestic water needs and for food production.[57] Rising sea level leads to a higher frequency of overwash events,[58] during which seawater inundates large parts of the islands and contaminates freshwater aquifers, wetlands, and other aquifer-fed environments. Overwash events already periodically occur during unusually high tides as a result of storm-driven waves or because of tsunamis. Rising sea level greatly increases the risk of groundwater contamination when these events occur.

Climate shifts have already been observed in the region, with increases in temperature and changes in rainfall. In Hawai'i, temperature has risen by 0.76°F over the past 100 years (Figure 27.5),[59] and 2015 and 2016 were the warmest years on record. Higher temperatures increase evaporation, reducing water supply and increasing water demand. Hawai'i rainfall has been trending downward for decades, with the period since 2008 being particularly dry.[60] These declines have occurred in both the wet and dry seasons and have affected all the major islands (Figure 27.6). In Micronesia, rainfall has generally decreased in the east, remained steady for some islands in the west (for example, Guam), and increased for other islands in the west.[23,32,61,62]

The set of global and regional climate model outputs available for the U.S. Pacific Islands region shows a range of possible future precipitation changes, with implications for economic and policy choices. In Hawai'i, end-of-century rainfall projections under a higher scenario (RCP8.5) range from small increases to increases of to up to 30% in wet areas, and from small decreases to decreases of up to 60% in dry areas.[34,35]

Using global climate model results for the lower scenario (RCP4.5) (see the Scenario Products section of App. 3), rainfall in Micronesia is projected to become as much as 10% lower to as much as 20% higher than at present within the next several decades, changes that are within the range of natural variability.[63] Changes are projected to be slightly greater by the end of the century but still within the –10% to +20% range for Micronesia.[63] In American Sāmoa, rainfall is projected to increase by up to 10% by mid-century compared with the present, with additional slight increases by the end of the century.

While rainfall in Hawai'i generally has been decreasing, it is also becoming more extreme.[64,65] Both extreme heavy rainfall

events (causing increased runoff, erosion, and flooding) and droughts (causing water shortages) have become more common.[66] The number of consecutive wet days and the number of consecutive dry days are both increasing in Hawai‘i.[66] In American Sāmoa, drought magnitude and duration have minimal decreasing trends.[23]

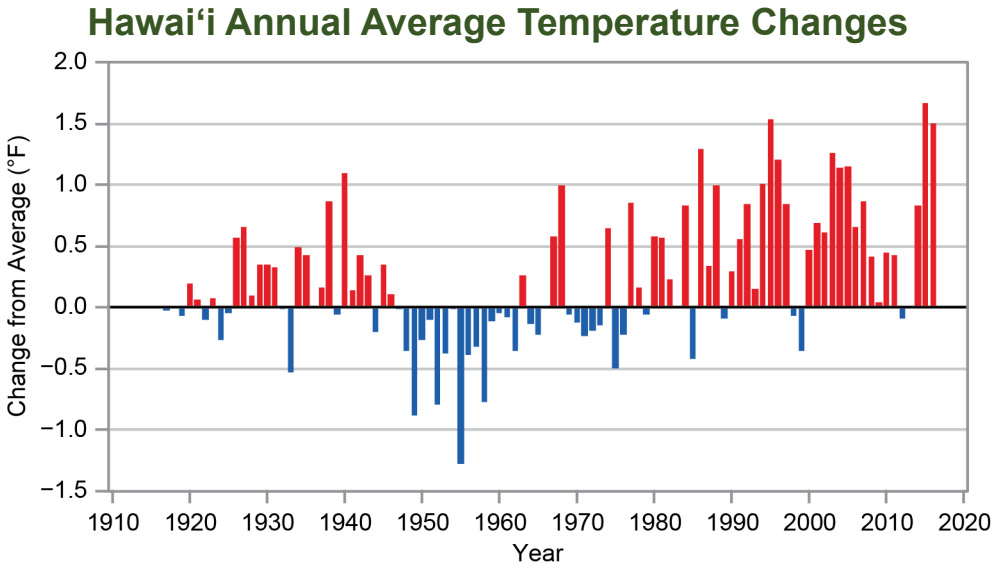


Figure 27.5: In Hawai‘i, annual average temperatures over the past century show a statistically significant warming trend, although both warming and cooling periods occurred. Based on a representative network of weather stations throughout the islands, this figure shows the difference in annual average temperature as compared to the average during 1944–1980 (this period was selected as the baseline because it has the greatest number of index stations available), with red bars showing years with above average temperatures and blue bars showing years with below average temperatures. As temperature continues to rise across the region and cloud cover decreases in some areas, evaporation is expected to increase, causing both reduced water supply and higher water demand. Source: University of Hawai‘i at Mānoa, Department of Geography and Environment.

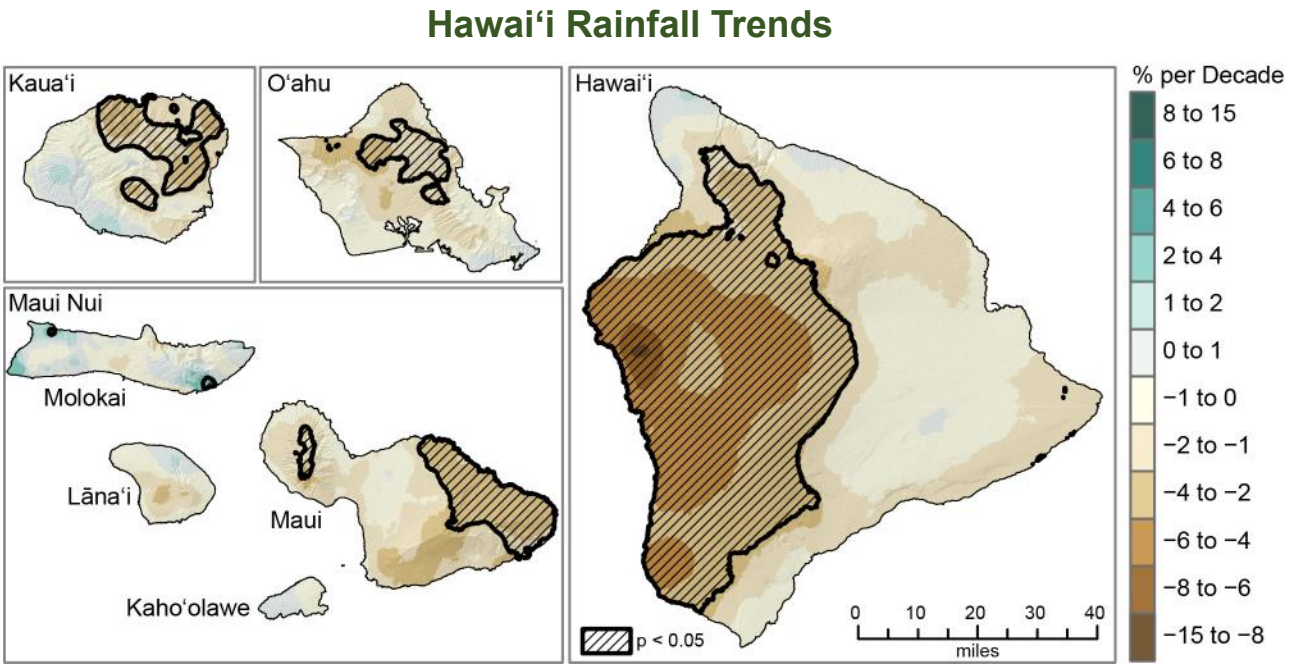


Figure 27.6: The figure shows the changes in annual rainfall (percent per decade) from 1920 to 2012 for the State of Hawai‘i. Statistically significant trends are indicated with black hatching. Almost the entire state has seen rainfall decreases since 1920. The sharpest downward trends are found on the western part of Hawai‘i Island. On other islands, significant decreases have occurred in the wetter areas. Source: adapted from Frazier & Giambelluca 2017.[60] © Royal Meteorological Society.

Higher rates of evaporation can strongly affect water resources by reducing the amount of water available (water supply) and by increasing the amount of water needed for irrigation and outdoor residential uses (water demand). Increasing temperatures throughout the Hawai'i–USAPI region and decreased cloud cover in some areas will cause increases in rates of evaporation. These increases will worsen effects of reduced rainfall by further reducing water supply and simultaneously increasing water demand.

Streamflow in Hawai'i has declined over approximately the past 100 years, consistent with observed decreases in rainfall.[6] Trends showing low flows becoming lower indicate declining groundwater levels. On islands such as O'ahu, water supply is mainly derived from groundwater.[67] If these declines continue due to further reductions in rainfall and/or increases in evaporation, groundwater availability will be impaired. Chronic water shortages are possible as rainfall decreases and both evaporation and the water requirements of a growing human population increase.

Given the small land areas and isolation of islands, and the current high level of year-to-year climate variability, even small changes in average climate are likely to cause extreme hardship. In the USAPI, subsistence-based agriculture persists, but the cultural and economic conditions that provided resilience have been eroded by the effects of colonization and globalization.[68] Hence, especially severe impacts of climate shifts are expected in these communities. Decreases in precipitation, together with saltwater contamination of groundwater systems due to sea level rise, threaten water and food security in some locations.[18,69,70]

Adaptation. Impacts and risks from climate change will vary due to differences in hydrological characteristics and the governance and adaptive capacity of each island. To address ongoing and future impacts of these changes, adaptive capacity can be enhanced by enabling individual island communities to identify and prioritize climate-related risks.[71] In Hawai'i, adaptation to address water shortages is already taking place through successful water conservation programs (see Case Study "Planning for Climate Impacts on Infrastructure"), watershed protection (Watershed Partnerships), drought planning (Commission on Water Resource Management), and changes in plumbing codes and policies (Fresh Water Initiative) to enhance groundwater recharge and wastewater reuse.[72,73]

In the USAPI, potential adaptation measures include development or improvement of emergency water shortage planning, including portable desalination systems and rapid-response drinking water shipments, although the high costs would prohibit larger desalination plants on most islands and atolls without international aid or other finance mechanisms.[74,75] Island communities can also improve their resilience to water shortages by increasing both rooftop water catchment and storage system capacity and by adopting drought-resistant and salt-tolerant crop varieties.

Throughout the region, the number of climate and water resources monitoring stations has declined,[23,76,77] reducing the ability of researchers to project future changes in climate. Restoring and enhancing monitoring of rainfall, evaporation-related climate variables (net radiation, air temperature, humidity, and wind speed), soil moisture, streamflow, and groundwater levels—critically important information for understanding, planning, and assessing adaptation actions—are prerequisites to building adaptive capacity to address the impacts of climate change on water resources.

Case Study: Planning for Climate Impacts on Infrastructure with the Honolulu Board of Water Supply (BWS)

The City and County of Honolulu Board of Water Supply (BWS) serves approximately one million customers on the island of O'ahu, Hawai'i, with about 145 million gallons per day (mgd) of potable (drinkable) groundwater and 10 mgd of nonpotable water.[78] The municipal system supports a large urban center, but the infrastructure is deteriorating.[78] Following the release of the 2012 Pacific Islands Regional Climate Assessment,[23] the BWS was concerned that changing climate patterns would affect both the quality and quantity of the water supply. Available projections showed increasing air temperature and drought risk,[23,34,35,36,60] reduced aquifer recharge, and coastal erosion that will impact wells and infrastructure.[41]

To proactively increase their capacity to respond and adapt to impacts of climate variability and change, the BWS was already implementing holistic long-term strategies to increase supply and lessen demand, including watershed management, groundwater protection, and a water conservation program. Because of these strategies, from 1990 to 2010, per capita use decreased from 188 to 155 mgd. However, total demand is still projected to increase 5% to 15% by 2040 due in part to population growth, with the most increases in areas of existing high population density.[78]

In 2015, the BWS partnered with researchers and consultants to assess projected climate change impacts on their infrastructure and to identify vulnerabilities over the next 20 to 70 years using a scenario planning approach to consider a range of plausible future climate and socioeconomic conditions. The vulnerability assessment considers extreme heat, coastal erosion, flooding (from wave overwash, sunny-day groundwater rise, and storms), annual and seasonal drought patterns, and changes in groundwater recharge impacts. As a project outcome, the BWS will develop a prioritized set of adaptive actions to minimize the range of climate impacts, including urgent capital improvements and updates to engineering standards.[79]

Key Message 2

Terrestrial Ecosystems, Ecosystem Services, and Biodiversity

Pacific island ecosystems are notable for the high percentage of species found only in the region, and their biodiversity is both an important cultural resource for island people and a source of economic revenue through tourism. Terrestrial habitats and the goods and services they provide are threatened by rising temperatures, changes in rainfall, increased storminess, and land-use change. These changes promote the spread of invasive species and reduce the ability of habitats to support protected species and sustain human communities. Some species are expected to become extinct and others to decline to the point of requiring protection and costly management.

Island landscapes and climates differ dramatically over short distances, producing a wide variety of ecological habitats and profoundly influencing the abundance and distribution of organisms, many of which have evolved to live in very specific environments and in close association with other species. Invasive species, landscape change, habitat alteration, and reduced resilience have resulted in extinctions and diminished ecosystem function (see Ch. 7: Ecosystems, KM 1).

The Hawaiian Islands illustrate the challenges the broader Pacific region is facing. Ninety percent of the terrestrial species native to Hawai'i are endemic (unique to the region). New, and potentially invasive, species are arriving much more frequently than in the past.[80,81] Hawai'i is home to 31% of the Nation's plants and animals listed as threatened or endangered, and less

than half of the landscape on the islands is still dominated by native plants.[82] A similar picture describes most of the USAPI, as well. For example, Guam is well known for the decimation of its birds by the accidental introduction of the brown tree snake.

Nesting seabirds, turtles and seals, and coastal plants in low-lying areas are expected to experience some of the most severe impacts of sea level rise.[83] As detailed in the following section, rising sea levels will both directly inundate areas near shorelines and cause low-lying areas to flood due to the upward displacement of shallow aquifers. Rising sea levels also increase the tendency of large waves to wash inland and flood areas with saltwater, making the soil unsuitable for many plants and contaminating the underlying aquifer so that the water is not fit for drinking or crop irrigation.

Atolls are projected to be inundated, impacting existing on-island ecosystems.[18] Atoll communities that depend on subsistence agriculture already experience loss of arable land for food crops such as taro and breadfruit,[70] along with the degradation of aquifers from sea level variability and extreme weather. Without dramatic adaptation steps, the challenges of sea level rise will likely make it impossible for some atolls to support permanent human residence. Wildlife that relies on coastal habitats will likely also be severely impacted. More than half of the global populations of several seabird species nest in the atolls and low islands of Northwestern Hawaiian Islands. In addition to the direct impact from the loss and degradation of habitat, Key Message 4 describes how these species are at risk from changes in prey availability and increasing land surface temperatures.[84]

On many Pacific islands, native mangroves are highly productive coastal resources that provide a number of ecosystem services, including storm protection and food and building materials for Indigenous and local communities. Mangroves also serve as fish nursery areas, trap land-based sediment that would otherwise flow to coral reefs,[85] and provide habitat for many species. They are important reservoirs of organic carbon, providing yet another ecosystem service.[86] Mangroves are already under threat from coastal development and logging. Climate change, particularly sea level rise, will likely add additional stress.[87,88]

The planning and economic implications for biodiversity management are substantial. The main islands of Hawai'i have more than 1,000 native plant species,[89] and many of these are vulnerable to future climate shifts. Projections under a higher scenario (RCP 8.5) suggest that by the end of the century, the current distributions of more than 350 native species will no longer be in their optimal growing climate range.[90] For example, 18 of 29 native species studied within Hawai'i Volcanoes National Park are projected to shrink in range, such that most of the high-priority areas managed to protect biodiversity are projected to lose a majority of the studied native species.[91] Approximately $2 million is spent annually to manage these areas (dollar year not reported),[92] so climate-driven changes in plant distribution would have significant consequences on the allocation of funds. A global analysis suggests that the displacement of native species would provide increased opportunities for the establishment and spread of invasive species and that biodiversity would decrease as a result.[93,94]

Throughout the Pacific, climate change will likely alter ecosystem services provided by agroforestry (the intentional integration of trees and shrubs into crop and animal farming systems to create environmental, economic, and social benefits). In American Sāmoa, the Republic of the Marshall Islands, and the Federated States of Micronesia, upland or inland forest services include substantial acreage in mixed agroforests (forests with

various trees, lower shrubs, and row crops used for food, building, and cultural practices).[95,96] Agroforest production is impacted by drought, flooding, soil and water salinization (increased salt content in low-lying areas), wind, disease, pests, and clearing for development.[70] Climate change is projected to exacerbate these impacts in complex patterns related to the stressors present in specific locations.

Increases in air temperature are projected to have severe negative impacts on the range of Hawaiian forest birds. Avian malaria currently threatens this iconic fauna except at high elevations, where lower temperatures prevent its spread. However, as temperatures rise, these high-elevation sites will become more suitable for malaria. Model projections suggest that even under moderate warming, 10 of 21 existing forest bird species across the state will lose more than 50% of their range by 2100 (Figure 27.7). Of those, 3 are expected to lose their entire ranges and 3 others are expected to lose more than 90% of their ranges,[43,97] making them of high concern for extinction.

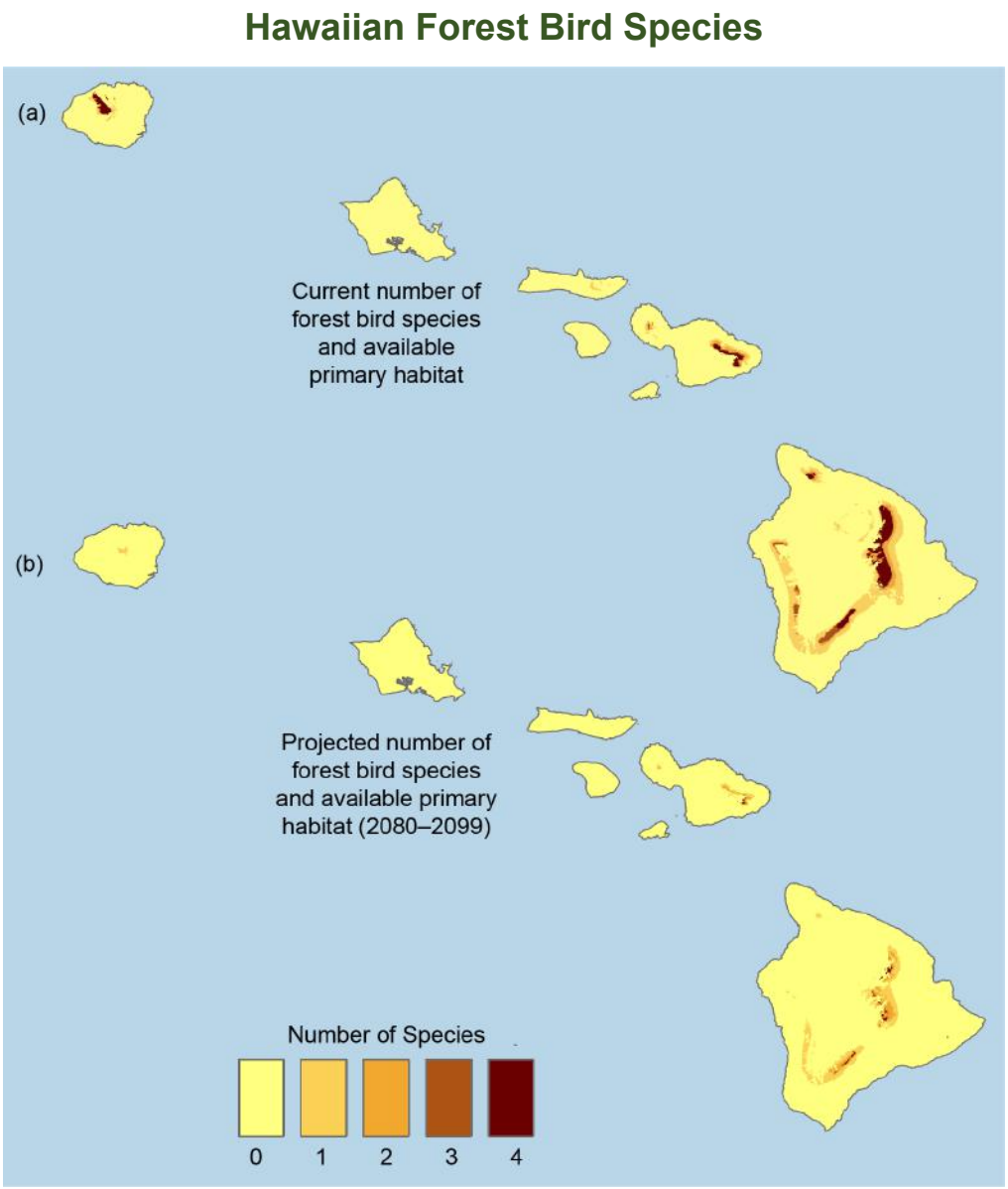


Figure 27.7: The figure shows the number of native Hawaiian forest bird species based on model results for (a) current and (b) future climate conditions. The future conditions are for the year 2100 using the middle-of-the-road scenario (SRES A1B). These projections include 10 species that represent the most rare and endangered native forest birds in Hawai'i. The number of these species and their available habitat are projected to be drastically reduced by 2100. Sources: adapted from Fortini et al. 2015[43] (CC BY 4.0).

Streams on U.S. Pacific Islands are also home to native fauna that are unique and typically restricted to specific island groups such as the Mariana, Sāmoan, and Hawaiian archipelagos. A model of streamflow and habitat on the Island of Maui suggests that physical habitat for stream animals will decrease by as much as 26% in some streams under a higher scenario (RCP8.5), but the overall forecast is for habitat changes of less than 5% by 2100.[98] Throughout Hawai'i, elevated stream water temperatures from urbanization and a warming climate will likely reduce available habitat for temperature-sensitive species. Additionally, the larvae of native Hawaiian stream animals develop in the ocean, and exposure to ocean acidification puts them at risk of physiochemical changes resulting in lower reproductive success.[99]

Adaptation. Adapting to the impacts of climate change on terrestrial ecosystems is challenging. Management measures can take years to design and fund. Currently, understanding specific impacts of climate change on a particular ecosystem is confounded by other stressors (such as land development and invasive species) and clouded by a lack of precision in forecasting how sea level, rainfall, and air temperatures will change at the ecosystem or habitat level. A recent report summarizes both vulnerabilities and potential adaptations across all Hawaiian Islands and ecosystem types.[100] Through research and collaboration with Indigenous communities and land managers, ecosystem resilience to climate change can be enhanced and the most severe climate change effects on biodiversity decreased.[101] Many Pacific island communities view the protection and management of native biodiversity as ways to reduce climate change impacts. For example, a watershed model of the windward side of Hawai'i Island suggested that control of an invasive tree with high water demand would partially offset decreases in streamflow that might be caused by a drier climate.[44] In another example, resource managers are now keenly aware that climate change represents a serious long-term threat to Hawaiian forest birds. As a result, discussions involving multiple federal, state, and nongovernmental organization stakeholders are underway regarding a range of management responses, such as shifting protected areas, landscape-level control of avian malaria, and captive breeding and propagation. Some of these discussions are focused on adaptation to many aspects of climate change, whereas others address the broad range of threats to Hawaiian forest birds. Preparedness and planning can strengthen the resilience of native species and ecosystems to drought, wildfire, and storm damage, which will help them to avoid extinction due to climate change.

Key Message 3

Coastal Communities and Systems

The majority of Pacific island communities are confined to a narrow band of land within a few feet of sea level. Sea level rise is now beginning to threaten critical assets such as ecosystems, cultural sites and practices, economies, housing and energy, transportation, and other forms of infrastructure. By 2100, increases of 1–4 feet in global sea level are very likely, with even higher levels than the global average in the U.S.-Affiliated Pacific Islands. This would threaten the food and freshwater supply of Pacific island populations and jeopardize their continued sustainability and resilience. As sea level rise is projected to accelerate strongly after mid-century, adaptation strategies that are implemented sooner can better prepare communities and infrastructure for the most severe impacts.

The rate of global average sea level rise has accelerated[102,103] and has become very damaging in the region (Figure 27.8). Impacts include coastal erosion,[7,8] episodic flooding,[9,10] permanent inundation,[11] heightened exposure to marine hazards,[12] and saltwater intrusion to surface water and groundwater systems.[13,14] Already apparent on many shorelines, these problems endanger human communities by negatively impacting basic societal needs, such as food and freshwater availability, housing, energy and transportation infrastructure, and access to government services.[104]

Sea level could rise by as much as 1 foot by 2050 and by as much as 4 feet by 2100. Emerging science suggests that, for the Extreme sea level rise scenario, sea level rise of more than 8 feet by 2100 is physically possible. It is extremely likely that sea level rise will continue beyond 2100.[17,105]

Communities in Hawai'i and the USAPI typically live in low-lying settings clustered around the coastal zone. Whether on high volcanic islands or low reef islands (atolls), exposure to marine hazards and dependency on global trade mean escalating vulnerability to climate change (Ch. 16: International, KM 1).[18]

Roadways Flood Periodically on O'ahu

Figure 27.8: The photo shows North Shore, O'ahu, in the winter of 2016. Episodic flooding in the Pacific Islands will increase as sea level rises. Photo credit: Steven Businger.

Until recently, global sea level rise of about 3 feet by the end of the century was considered a worst-case scenario, becoming more likely without reductions in global greenhouse gas emissions.[106] However, new understanding about melting in Antarctica,[107,108,109] Greenland,[110] and alpine ice systems;[111] the rate of ocean heating;[112,113] and historical sea level trends[103] indicates that it is physically possible to see more than double this amount this century (see Ch. 2: Climate, KM 4).[17,114]

The Intermediate sea level rise scenario predicts up to 3.2 feet of global sea level rise by 2100; however, recent observations and projections suggest that this magnitude of sea level rise is possible as early as 2060 in a worst-case scenario.[17] Studies in Hawai'i show that the value of all structures and land projected to be flooded by 3.2 feet of sea level rise amounts to more than $19 billion (in 2013 dollars; $19.6 billion in 2015 dollars) statewide (Figure 27.9).[42] Across the state, nearly 550 Hawaiian cultural sites would be flooded or eroded, 38 miles of major roads would be chronically flooded, and more than 6,500 structures and 25,800 acres of land located near the shoreline would be unusable or lost, resulting in approximately 20,000 displaced residents in need of homes.[42]

Potential Economic Loss from Sea Level Rise, O'ahu, Hawai'i

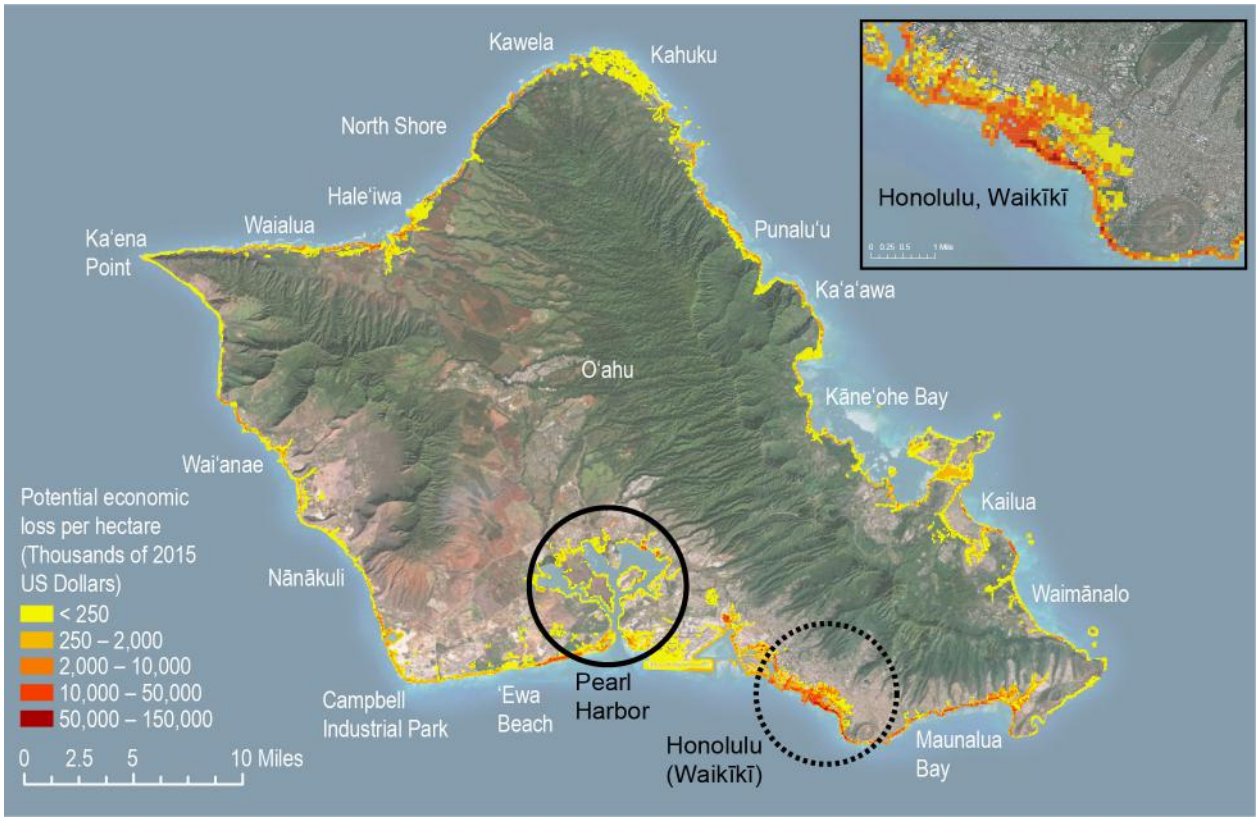


Figure 27.9: This map highlights potential economic losses (in 2015 dollars) in the exposure area associated with 3.2 feet of sea level rise on the island of O'ahu, Hawai'i. Potential economic losses are estimated from impacts to land and residential and commercial infrastructure. Highly impacted areas at risk of large economic losses include the U.S. Pacific Command and military infrastructure concentrated in Pearl Harbor (black circle) and the vulnerable tourist areas surrounding Waikīkī (dashed black circle). Source: adapted by Tetra Tech Inc. from the Hawai'i Climate Change Mitigation and Adaptation Commission 2017.[42]

Owing to global gravitational effects, sea level rise will disproportionately affect the tropical Pacific[15] and potentially exceed the global average.[16] This, plus sea level variability internal to the Pacific Basin (see Figure 27.3), means that parts of the region are likely to experience the highest rates of sea level rise on the planet.[115] Scientific understanding of the timing and magnitude of future global sea level rise continues to improve,[116,117] making regular updates of management plans and engineering codes an important activity for island communities.

Because of accelerating sea level rise, coastal communities are projected to experience saltwater intrusion of aquifers and agricultural resources. As sea level rise continues in coming decades, freshwater sources will become increasingly at risk in communities dependent on restricted groundwater supplies.[69] Saltwater intrusion, which is amplified by climate variability and changing precipitation patterns (see Key Message 1),[12] is difficult to prevent, and, once damaged, water and food resources are challenging to restore.[13]

Future changes in global and regional precipitation vary among current climate models,[34,35,118] but the potential for changes in precipitation and the projected impacts of saltwater intrusion cast uncertainty over the sustainability of freshwater resources throughout the region. Because many island groups are very isolated, severe drought punctuated by saltwater intrusion can displace communities and produce feedback effects, such as failure of cultural, health, education, and economic systems (Ch. 17: Complex Systems).[119] However, strategic planning for the inevitability of these events can greatly reduce their impact.

In many areas, Pacific island coastal populations already exist on the edge of sustainability. Urban areas typically cluster around port facilities, as nearly all Pacific communities are tied to goods and services delivered by cargo ships. As the world's most isolated chain of islands, Hawai'i imports nearly 90% of its food at a cost of more than $3 billion per year (in 2004–2005 dollars),[120] resulting in government programs focused on food security.[121] Without adaptation measures, the additional stress on sustainable practices related to sea level rise is likely to drive islanders to leave the region and make new homes in less threatened locations (see Key Message 6 and Case Study "Bridging Climate Science and Traditional Culture").[122]

Away from urban areas, many island communities rely on food gathered from the ocean and land. Populations on remote reef islands throughout Micronesia depend on water, food, and medical assistance that are often in question and are a source of persistent community stress. Extreme water levels accompanied by high waves have swept over remote atoll communities and destroyed taro patches, contaminated fragile aquifer systems, and deeply eroded island shores.[9,10,58]

In 2007, extreme tides coupled with high waves flooded the Federated States of Micronesia and triggered a national emergency. Food, water, and medical supplies had to be immediately delivered to dozens of communities in widely distributed locations to prevent famine (see Key Message 1) (see also Ch. 14: Human Health, KM 1).[57] It is likely that events of this type will increase in frequency as sea level rise accelerates in the future.

Rising sea surface temperatures are shifting the location of fisheries (Ch. 9: Oceans, KM 2).[123] Ocean warming [124] and acidification,[125,126] coupled with damaging watershed[127] and reef practices,[128] converge on island shores to increasingly limit the food resources that can be gathered from the sea (see Key Message 4).[129] Growing exposure to coastal hazards,

such as storm surges,[130] compounds this threat to sustainability.

The Pacific Ocean is highly variable; fundamental characteristics of ENSO (see Box 27.1) appear to be changing.[131] Both El Niño and La Niña episodes are projected to increase in frequency and magnitude as the world warms.[3,52] Patterns of variability are complex,[132,133] and as climate changes over the long term, the oceanic and atmospheric forces that cause shorter-term climate variability (such as ENSO) also will be changing. Model projections indicate changing future wave conditions that will vary in complex ways spatially, by season, and with shoreline exposure and orientation.[37,38,134] These changes will challenge community efforts to define adaptation plans and policies.

The 2015–2016 El Niño was a Pacific-wide event with widespread impacts.[135] As warm water shifted from west to east, Palau, Yap, and other western Pacific communities experienced deep drought, requiring water rationing, as well as falling sea level that exposed shallow coral reefs.[136] In the central Pacific, Hawai'i experienced 11 days of record-setting rainfall that produced severe urban flooding,[137] while American Sāmoa faced long-term dry conditions punctuated by episodic rain events. Honolulu experienced 24 days of record-setting heat that compelled the local energy utility to issue emergency public service announcements to curtail escalating air conditioning use that threatened the electrical grid (Ch. 4: Energy, KM 1).[138] Nine months of drought stressed local food production, and a record tropical cyclone season saw Hawai'i monitoring three simultaneous hurricanes at one point.[139]

There is great uncertainty about how Pacific variability occurring on shorter timescales (for example, El Niño and La Niña) will combine with multidecadal changes in temperature, waves, rainfall, and other physical factors. This variability affects sea level extremes, which are likely to become more frequent this century,[4,12] along with changes in precipitation,[140] ocean temperature,[113] and winds.[141] These, in turn, drive difficult-to-forecast stressors that challenge the sustainability of coastal communities.

To date, tropical cyclone frequency and intensity have not been observed to change in the region of the USAPI. Trade winds and monsoon wind characteristics are expected to change in the future, but projections for specific geographic locations are unclear.[142] Under scenarios with more warming (for example, SRES A1B),[143] wind speeds are projected to decrease in the western Pacific and increase in the South Pacific;[142] central Pacific tropical cyclone frequency and intensity are expected to increase;[40,142] and in the western and South Pacific, tropical cyclone frequency is projected to decrease, while cyclone intensity is projected to increase.[142] Combined with continued accelerations in sea level rise, storm surge associated with a tropical cyclone has the potential to deliver a profound shock to a community beyond any ability to meaningfully recover.

Adaptation. Despite these threats, many Pacific communities are growing more resilient with renewed focus on conservation,[144] sustainably managing natural resources,[145] adapting to climate change,[146] and building more resilient systems.[147] Pacific island governments are taking steps to anticipate marine flooding (securing food and water resources) and doing so in the context of environmental conservation. Islanders throughout the USAPI are committing to demonstrate climate leadership, identifying sector vulnerabilities, and calling on their international partners to support their implementation of climate change resilience and adaptation actions.[55,148,149,150,151,152]

Key Message 4

Oceans and Marine Resources

Fisheries, coral reefs, and the livelihoods they support are threatened by higher ocean temperatures and ocean acidification. Widespread coral reef bleaching and mortality have been occurring more frequently, and by mid-century these events are projected to occur annually, especially if current trends in emissions continue. Bleaching and acidification will result in loss of reef structure, leading to lower fisheries yields and loss of coastal protection and habitat. Declines in oceanic fishery productivity of up to 15% and 50% of current levels are projected by mid-century and 2100, respectively, under the higher scenario (RCP8.5).

The ocean around Hawai'i and the USAPI supports highly diverse marine ecosystems that provide critical ecosystem services.[123] Coral reef ecosystems are vitally important for local subsistence, tourism, and coastal protection. The pelagic (open ocean) ecosystem supports protected species, including sea turtles, sea birds, and marine mammals, as well as economically valuable fisheries for tunas and other pelagic fishes. In Hawai'i, for example, coral reefs inject an estimated $364 million in goods and services annually (in 2001 dollars) into the local economy,[19] while the landings from the pelagic longline fisheries are worth over $100 million annually (in 2012–2013 dollars).[153]

Climate change is already being observed in the Pacific Ocean. Sea surface temperatures and ocean pH, an indicator of acidity, are now beyond levels seen in the instrument record.[154] Additionally, oxygen levels in the subtropical Pacific have been declining over the past five decades, negatively impacting fishes that draw oxygen from the water.[155] Impacts from sea level rise on coastal habitats and infrastructure have already occurred in the region, and the rate of sea level rise is projected to accelerate (see Key Message 3).

Widespread coral bleaching and mortality occurred during the summers of 2014 and 2015 in Hawai'i and during 2013, 2014, and 2016 in Guam and the Commonwealth of the Northern Mariana Islands. Impacts varied by location and species, but the 2015 bleaching event resulted in an average mortality of 50% of the coral cover in western Hawai'i.[45] Coral losses exceeded 90% at the remote and pristine equatorial reef of Jarvis Island.[156]In response to the prolonged and widespread bleaching, the State of Hawai'i convened an expert working group to generate management recommendations to promote reef recovery.[157]

Under projected warming of approximately 0.5°F per decade, coral reefs will experience annual bleaching beginning in about 2035 in the Mariana Archipelago, in about 2040 in American Sāmoa and the Hawaiian Islands, and in about 2045 at other equatorial reefs (Figure 27.10).[46] Warming reductions on the order of the aims of the 2015 Paris Agreement are projected to delay the onset of annual severe bleaching by 11 years on average.[46] Because some coral species are more resilient to thermal stress than others, low levels of thermal stress are expected to only alter the types of corals present. However, at high levels of thermal stress, most coral species experience some bleaching and mortality.[158] Ocean acidification reduces the ability of corals to build and maintain reefs,[125,159] while land-based nutrient input can substantially exacerbate acidification and reef erosion.[160] Under the higher scenario (RCP8.5), by the end of the century, virtually all coral reefs are projected to experience an ocean acidification level that will severely compromise their ability to grow.[125,161] Loss of coral reef structure results in a decline in fish

abundance and biodiversity, negatively impacting tourism, fisheries, and coastal protection.[123] In the Hawaiian Archipelago under the higher scenario (RCP8.5), coral reef cover is projected to decline from the present level of 38% to 11% in 2050 and to less than 1% by the end of the century. This coral reef loss is projected to result in a total economic loss of $1.3 billion per year in 2050 (in 2015 dollars, undiscounted) and $1.9 billion per year in 2090 (in 2015 dollars, undiscounted). In 2090, the lower scenario (RCP4.5) would avoid 16% of coral cover loss and $470 million in damages per year (in 2015 dollars, undiscounted) compared to the higher scenario (RCP8.5).[162] In the central and western Pacific, coral reef cover is projected to decline by 2050 from a present-day average of 40% to 10%–20%, and coral reef fish production is expected to decline by 20% under a high emissions scenario (SRES A2).[123] Declines in maximum catch potential exceeding 50% from late-20th century levels under the higher scenario are projected by 2100 for the exclusive economic zones (EEZs) of most islands in the central and western Pacific.[163] A key uncertainty is the extent to which corals can develop resilience to the rapidly changing ocean conditions.[164,165] Changing ocean temperature and acidification will impact many other organisms that will likely alter the functioning of marine ecosystems.

Projected Onset of Annual Severe Coral Reef Bleaching

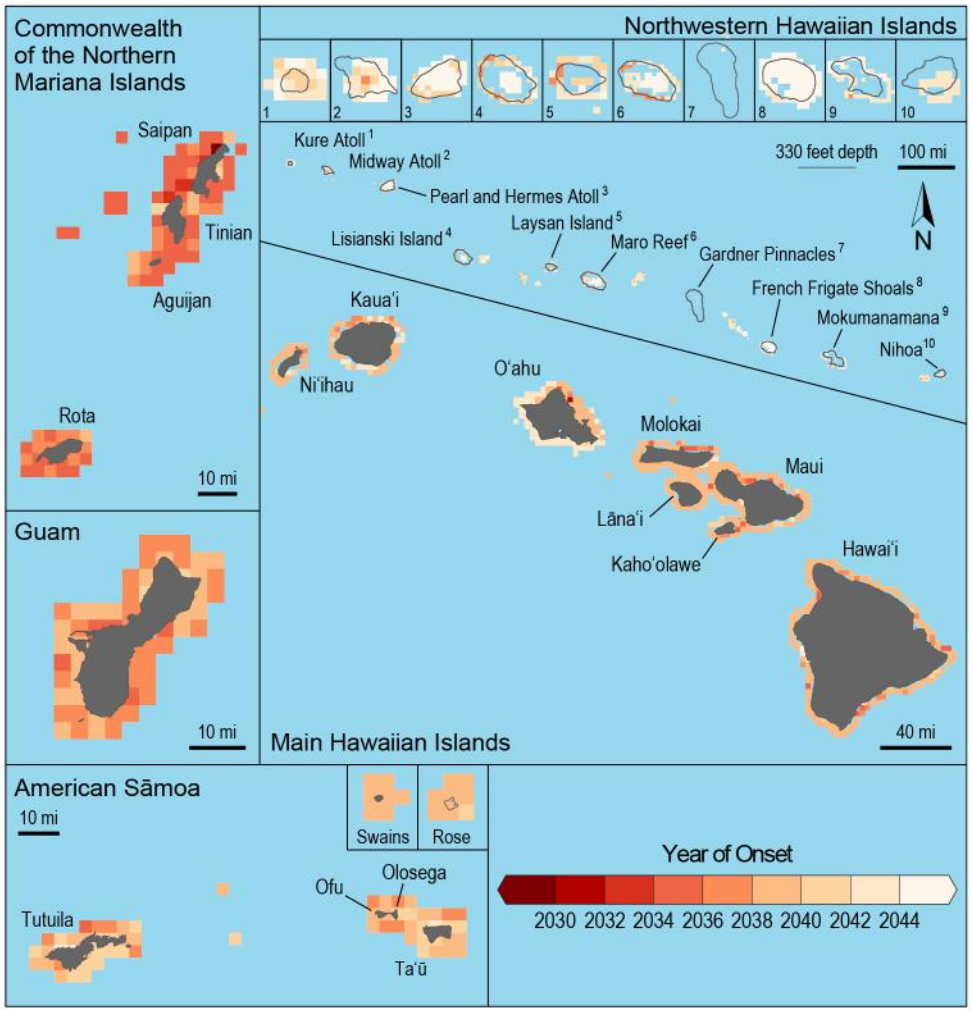


Figure 27.10: The figure shows the years when severe coral bleaching is projected to occur annually in the Hawai'i and U.S.-Affiliated Pacific Islands region under a higher scenario (RCP8.5). Darker colors indicate earlier projected onset of coral bleaching. Under projected warming of approximately 0.5°F per decade, all nearshore coral reefs in the region will experience annual bleaching before 2050. Source: NOAA.

Mangroves provide coastal protection and nursery habitat for fishes and, in some cases, protect coral reefs from sediment and enhance the density of coral reef fishes.[166] Sea level rise has caused the loss of mangrove areas at sites in American Sāmoa[87] and is projected to further reduce mangrove area in the Pacific Islands region by 2100.[87,88]

In the open ocean, warming is projected to reduce the mixing of deep nutrients into the surface zone. Under the higher scenario (RCP8.5), increasing temperatures and declining nutrients are projected to reduce tuna and billfish species' richness and abundance in the central and western Pacific Ocean, resulting in declines in maximum fisheries yields by 2%–5% per decade.[129,167,168,169] Climate change is also projected to result in overall smaller fish sizes, further adding to the fishing impact (Ch. 9: Oceans, KM 2).[170]

Tuna habitat in the equatorial region is projected to shift eastward with changing temperatures, so that by the end of the century the availability of skipjack tuna within the EEZs of Micronesian countries will likely be 10%–40% lower than current levels.[123]

On low-lying islands and atolls, sea level rise is projected to result in the loss of resting and nesting habitat for sea birds and sea turtles and the loss of beach and pupping habitat for Hawaiian monk seals. Modeling exercises that take wave height into account project much greater habitat flooding than sea level rise alone would suggest.[18,38,171] For example, sea level rise of about 6 feet combined with both storm wave run-up and concurrent groundwater rise is projected to wash out 60% of the albatross nests across the U.S. Marine National Monuments each breeding season.[83]

Adaptation. Management actions that remove other stressors on corals (such as those recommended in Hawai'i, Guam, and the Commonwealth of the Northern Mariana Islands after the recent bleaching events) have been proposed as strategies to enhance the resilience of corals to moderate levels of thermal stress and to aid their recovery.[157] However, experience from the 2016 extreme bleaching on the Great Barrier Reef found that water quality and fishing pressure had minimal effect on the unprecedented bleaching, suggesting that local reef protection measures afford little or no defense against extreme heat.[158] This suggests that more active intervention is necessary, such as incorporating assisted evolution and selectively breeding corals, to enhance their resilience to rapidly rising ocean temperatures and acidification,[172] as is being tested in Hawai'i. In the case of the pelagic ecosystem, fishing and climate change work together to reduce the abundance of tunas and billfishes targeted by the fishery.[170,173] Thus, an ecosystem-based approach to international management of open ocean fisheries in the Pacific that incorporates climate-informed catch limits is expected to produce more realistic future harvest levels and enhance ecosystem resilience.[20] Lastly, relocations of seabirds to nesting sites on higher islands have been proposed to mitigate lost nesting habitat on low-lying islands and atolls.[83]

Key Message 5

Indigenous Communities and Knowledge

Indigenous peoples of the Pacific are threatened by rising sea levels, diminishing freshwater availability, and shifting ecosystem services. These changes imperil communities' health, well-being, and modern livelihoods, as well as their familial relationships with lands, territories, and resources. Built on observations of climatic changes over time, the transmission and protection of traditional knowledge and practices, especially via the central role played by Indigenous women, are intergenerational, place-based, localized, and vital for ongoing adaptation and survival.

Indigenous communities of the Pacific have an inseparable connection to and derive their sense of identity from the lands, territories, and resources of their islands. This connection is traditionally documented in genealogical chants and stories transmitted through oral history.[146] The rich cultural heritage of Pacific island communities comprises spiritual, relational, and ancestral interconnectedness with the environment[174] and provides land security, water and energy security, livelihood security, habitat security,[175] and cultural food security.[176] Climate change threatens this familial relationship with ancestral resources[177] and is disrupting the continuity that is required for the health and well-being of these communities (this experience is common to many tribal and Indigenous communities across the United States) (see Ch. 15: Tribes, KM 2).[176,177]

Sea level rise imperils Indigenous communities of the Pacific. The sea that surrounds Pacific island communities continues to rise at a rate faster than the global average,[115] with documented impacts on agriculture, coastal infrastructure, food security, livelihoods, and disaster management in the Republic of Palau[149] and the Republic of the Marshall Islands.[147]

In Hawai'i, sea level rise impacts on traditional and customary practices (including fishpond maintenance, cultivation of salt, and gathering from the nearshore fisheries) have been observed (Figure 27.11).[177] Since 2014, Indigenous practitioners have had limited access to the land where salt is traditionally cultivated and harvested due to flooding and sea level rise. Detachment from traditional lands has a negative effect on the spiritual and mental health of the people (Ch. 14: Human Health, KM 1; Ch. 15 Tribes, KM 2).[176]

Salt Cultivation on Kaua'i

Figure 27.11: Flooding on the island of Kaua'i, Hawai'i, impacts the cultural practice of pa'akai (salt) cultivation. Photo credit: Malia Nobrega-Olivera.

Case Study: Bridging Climate Science and Traditional Culture

To identify adaptive management strategies for Molokai's loko i'a (fishponds) built in the 15th century, the nonprofit Ka Honua Momona's fishpond restoration project gathered Hawai'i's climate scientists, Molokai's traditional fishpond managers, and other resource managers to share knowledge from different knowledge systems (Figure 27.12). Loko i'a are unique and efficient forms of aquaculture that cultivate pua (baby fish) and support the natural migration patterns over the life of the fish. The lens of the ahupua'a (the watershed, extending from the uplands to the sea) was an important framework for this project. Sea level rise, surface water runoff, and saltwater intrusion into the freshwater springs are a few of the climate change impacts to which fishponds are vulnerable.[177] A key outcome of creating this collaborative model was strengthening relationships between diverse groups of people committed to responding to ecosystem changes and protecting cultural and natural resources.

Preparing Molokai's Fishponds for Climate Change

Figure 27.12: Ka Honua Momona hosted Molokai's loko i'a managers, Hawai'i's climate scientists, and other resource managers in April 2015. Photo credit: Hau'oli Waiau.

Ocean acidification and drought, in combination with pollution and development, are negatively affecting fisheries and ecosystems (which are drivers of tourism), directly impacting the livelihood security of Pacific communities. For example, across all Pacific island countries and territories, industrial tuna fisheries account for half of all exports, 25,000 jobs, and 11% of economic production.[178] In Hawai'i, between 2011 and 2015, an annual average of 37,386 Native Hawaiians worked in tourism-intensive industries; based on the 2013 U.S. census, this number represents 12.5% of the Native Hawaiian population residing in Hawai'i.

Climate change is impacting subsistence[18,70,95,123,175] and cultural food security[70,176] of Pacific island communities. Subsistence food security is essential for the survival of Indigenous peoples of the world and is valued socially, culturally, and spiritually.[175] Cultural food security refers to the provision of food that is a necessary part of a community's regular diet and sustains the connection with cultural and social practices and traditions.[176] Taro and fish are two examples of cultural foods important to the livelihoods of Pacific island communities and to economic development for the community and government.[123]

In Hawai'i, climate change impacts, such as reduced streamflow, sea level rise, saltwater intrusion, and long periods of drought, threaten the ongoing cultivation of taro and other traditional crops.[177] Identifying and developing climate-resilient taro and other crops are critical for their continued existence.[179] In Yap, taro is a key element of the diet. Groundwater salinization has resulted in smaller corms (underground tubers), causing declines in harvest yield.[180] In American Sāmoa, the Republic of the Marshall Islands, and the Federated States of Micronesia, crops grown in mixed agroforests provide important sources of nutrition, meet subsistence needs, supplement household incomes through sales at local farmers' markets, and support commercial production.[95,96] These crops include breadfruit, mango, and coconut as overstory components; citrus, coffee, cacao, kava, and betel nut as perennial components; and banana, yams, and taro. Climate change is expected to result in changes in farming methods and cultivars (Figure 27.13). Consequently, these changes will likely impact the relationship between communities and the land. These kinds of climate impacts lead to an increased dependence on imported food that is of little nutritional value.[181] This is a public health concern for Hawai'i and the USAPI, as Indigenous Pacific Islanders have the highest rates of obesity and chronic diseases, such as diabetes, in the region.[182]

The rich body of traditional knowledge is place-based and localized[21] and is useful in adaptation because it builds on intergenerational sharing of observations[22] of changes in climate-related weather patterns, ocean phenomena, and phenology (the study of cyclic and seasonal natural phenomena, especially in relation to climate and plant and animal life). These observations, gathered over millennia, are useful in defining baselines and informing adaptive strategies.[183] Indigenous cultures are resilient, and their resilience has empowered Pacific island communities to survive several millennia on islands.[180] These communities have survived extreme events and responded to change through adaptive mechanisms based on traditional knowledge that has evolved over many generations.[184]

Women play a vital role in ensuring that adaptation planning and action in the Pacific draw on traditional knowledge and new technologies.[184] The role of women in Indigenous communities includes maintaining crop diversity as collectors, savers, and managers of seeds and thus enhancing livelihood security for the community.[185] Indigenous women are also central in teaching, practicing, protecting, and transmitting traditional knowledge and practices.[185] Women have also been identified as a more vulnerable population to regional climate risks due to the role they have in terms of economic activities, safety, health, and their livelihoods.[147] For example, in Palau, as in the broader region, the central role of Indigenous women as lead project participants is key to the success of any project.

In Pacific island cultures, lunar calendars are tools used to identify baselines of an environment, track changes (kilo, in Hawaiian), and

Crop Trials of Salt-Tolerant Taro Varieties

Figure 27.13: Taro trials are underway in Palau, with results so far indicating that three varieties have tolerance to saltwater. Photo credit: Malia Nobrega-Olivera.

record seasonality, migration patterns, and weather.[183] In Hawai‘i, use of the traditional lunar calendar (kaulana mahina) and kilo in climate change adaptation assists communities with decision-making that allows for the best survival techniques.[183] In Mo‘omomi, Molokai, an intact coastal sand dune ecosystem in the main Hawaiian Islands, kaulana mahina has proven to be a useful tool that has enhanced the resilience of this coastline.[186,187] Similarly, a calendar for traditional Marshallese agroforestry crops recently was adapted to account for ENSO and climate conditions (see Figure 27.14).[188]

Emerging issues for Indigenous communities of the Pacific include the resilience of marine-managed areas and climate-induced human migration from their traditional lands, territories, and resources. Marine-managed areas, such as those designated under the Micronesia Challenge and the Papahānaumokuākea Marine National Monument in Hawai‘i, demonstrate a commitment by multiple partners to conserve marine resources. Over time, monitoring the ability of Indigenous peoples to continue to experience kinship and maintain traditional practices can help to preserve the cultural heritage associated with these protected areas. Documenting the kinds of governance structures or decision-making hierarchies created for their management can serve as a learning tool that can be shared with other island communities.

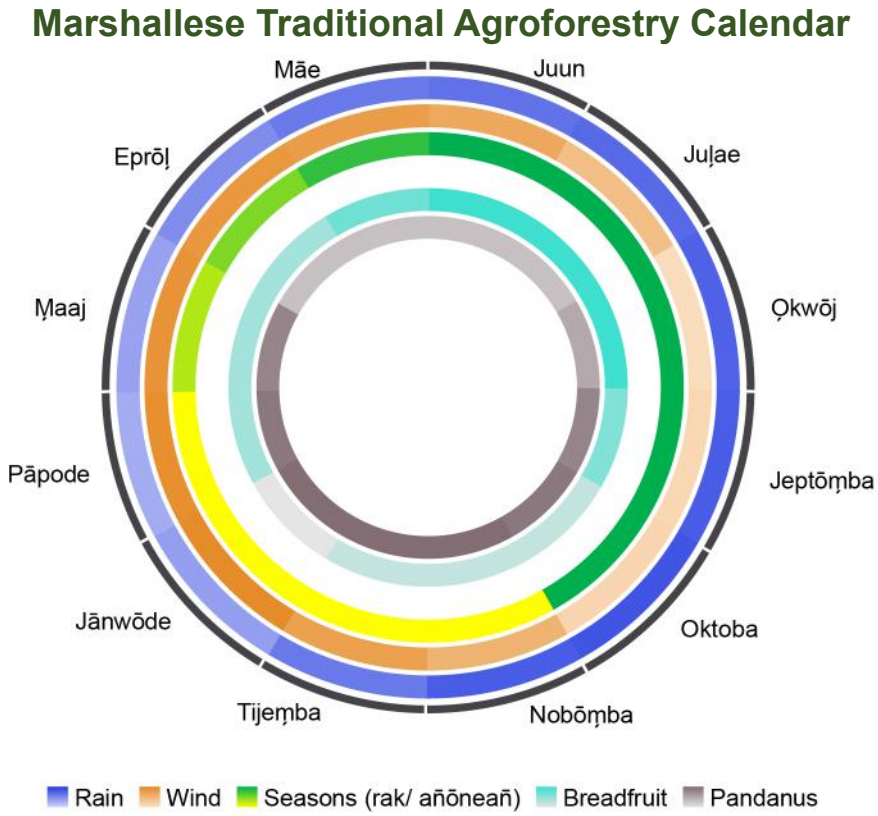


Figure 27.14: The Marshallese Traditional Agroforestry Calendar combines climate data and traditional season designations and knowledge about the harvest times of perennial crops throughout the year. Months are displayed in Marshallese on the outer ring, while inner rings show how wind and rain patterns and the harvest of two crops typically change throughout the year. The color gradients show the intensity of the harvest or the climate variable, with more intense colors representing larger amounts harvested or higher amounts of rain, for example, at various times. A web-based tool offers two versions, depending on the status of ENSO conditions. Source: adapted by Victor Garcia, Jr., from Friday et al. 2017.[188]

Key Message 6

Cumulative Impacts and Adaptation

Climate change impacts in the Pacific Islands are expected to amplify existing risks and lead to compounding economic, environmental, social, and cultural costs. In some locations, climate change impacts on ecological and social systems are projected to result in severe disruptions to livelihoods that increase the risk of human conflict or compel the need for migration. Early interventions, already occurring in some places across the region, can prevent costly and lengthy rebuilding of communities and livelihoods and minimize displacement and relocation.

Sectoral impacts act together to compound environmental, social, cultural, and economic costs. Pacific islands are particularly vulnerable to climate change impacts due to their exposure and isolation, small size, low elevation (in the case of atolls), and concentration of infrastructure and economy along the coasts. The interconnectedness of people in island communities and the interdependence between human activities and the natural environment[119] mean that extreme events cause multiple, layered impacts, intensifying their effects (see Ch.17: Complex Systems). While each of these impacts presents challenges, when combined, the environmental, social, cultural, and economic impacts will have compounding costs. In addition, as some types of extreme events become more frequent, recovery from those events will prove increasingly difficult

for isolated, resource-challenged islands,[189] resulting in long-term declines in people's welfare.[190,191]

Coastal flooding is a widely recognized threat to low-lying areas (see Key Message 3).[7] Extreme sea level events—created by combinations of factors such as storm-generated waves, storm surges, king tides, and ENSO-related sea level changes (see Box 27.1), combined with ongoing sea level rise—pose multiple challenges to habitability; on atolls, they are a clear threat to communities' existence (Figures 27.15, 27.16, 27.17). In 2005, when Cyclone Percy hit the Northern Cook Islands, waves swept across the atoll from both the ocean and the lagoon sides. Fresh food supplies were destroyed due to saltwater intrusion into taro fields, 640 people were left homeless, and freshwater wells were polluted, posing a risk to public health. Saltwater contamination of the freshwater lenses lasted 11 months or longer.[13] In Tokelau, Cyclone Percy scattered human waste, trash, and other debris into the ocean and across the island. Tokelau's three atolls lost most of their staple crops, while fish habitats were destroyed.[192] The islands suffered beach erosion, and many live coral formations were covered by sand and debris. In addition, the storm damaged many of the hospitals, making treatment of the injured or displaced difficult.[193] Lack of technology and resources limits small islands' ability to adapt to these complex threats. The cascading effects on infrastructure, health, food security, and the environment result in significant economic costs.[194,195]

Sea level rise, the deterioration of coral reef and mangrove ecosystems (see Key Message 4), and the increased concentration of economic activity will make coastal areas more vulnerable to storms (see Key Message 3).[196] Pacific Islands already face underlying economic vulnerabilities and stresses caused by unsustainable development, such as the use of beaches for building materials that results in coastal erosion or the waste disposal on mangroves and reefs that undermines critical ecological functions. The compounding impacts of climate change put the long-term habitability of coral atolls at risk, introducing issues of sovereignty, human and national security,[197] and equity,[198,199,200] a subject of discussion at the international level.

An increase in the incidence of vector-borne diseases such as malaria and dengue in the Pacific Islands has been linked to climate variability and is expected to increase further as a result of climate change (see Ch. 14: Human Health, KM 1).[201,202] For example, in late 2013 and early 2014, Fiji experienced the largest outbreak of dengue in its history, with approximately 28,000 reported cases.[203]

Climate change impacts on ecological and social systems are already negatively affecting livelihoods[204,205,206] and undermining human security.[191,207] In some cases, changes in climate increase the risk of human conflict (see Ch. 16: International, KM 3).[191,207,208] However, exactly how and when these changes can lead to conflict needs further study.[208] Climate change poses a threat to human security through direct impacts on economies and livelihoods that aggravate the likelihood of conflict and risk social well-being.[209] For example, climate change puts ongoing disputes over freshwater in Hawai'i at risk of intensifying in the absence of policy tools to help resolve conflicts.[23] Human conflict in the Asia Pacific region is expected to increase as unequal resource distribution combines with climate impacts to affect communities that are heavily dependent on agriculture, forestry, and fishing industries.[210]

Flooding in Kosrae

Figure 27.15: A combination of heavy rain, exceptionally high tides, and waves caused flooding in Kosrae, the Federated States of Micronesia, in February 2017. Photo credit: Delia Sigrah.

Reservoirs in the Marshall Islands

Figure 27.16: A series of reservoirs that provide the main water supply on Majuro Atoll in the Republic of the Marshall Islands are filled with runoff from the Majuro airport runway. The water supply is vulnerable to drought and saltwater overwash from both the lagoon and ocean (pictured). Photo credit: Majuro Water and Sewer Company.

A Marshall Islands Storm

Figure 27.17: An unseasonable storm hit the Marshall Islands on July 3rd, 2015. Storms this strong historically have been rare in the Marshall Islands, but the frequency of the most intense of these storms is projected to increase in the western North Pacific in the future. Photo credit: Marshall Islands Journal.

Climate change is already contributing to migration of individuals and communities.[211,212] In March 2015, Marshall Islands Bikinian people gathered to discuss resettlement because of increased flooding from high tides and storms that was making the atoll of Kili uninhabitable (see Case Study "Understanding the Effect of Climate Change on the Migration of Marshallese Islanders").[213]

Climate change induced community relocation, a recognized adaptation measure, results in disruption to society–land relationships and loss of community identity.[214] Resettlement has resulted in people facing landlessness, homelessness, unemployment, social marginalization, food insecurity, and increased levels of disease.[122]

Inaction to address climate-related hazards is projected to lead to high economic costs that are preventable.[205] Remote island communities that are unprepared for extreme events would face disruptions of goods and services that threaten lives and livelihoods. Rebuilding is expensive and lengthy.[13,218,219,220] Further, due to the special connections Indigenous people have to ancestral lands and territories, any loss of these resources is a cultural loss (see Key Message 5).[221]

Case Study: Understanding the Effect of Climate Change on the Migration of Marshallese Islanders

As one of the lowest-lying island nation-states in the world, the Republic of the Marshall Islands (RMI) is acutely vulnerable to sea level rise, flooding, and the associated intrusion of saltwater into crucial freshwater supplies, traditional agriculture, and forestry. The number of Marshallese residing in the United States (excluding the U.S. Territories and Freely Associated States) has rapidly risen over the past decade, from 7,000 in 2000 to 22,000 in 2010,[215] which is equal to over 40% of RMI's current total population. There is also substantial internal migration, predominantly from outer islands to the main atoll of Majuro.[216,217] Whether migration is a potentially successful adaptation strategy is unknown. The factors triggering human migration are complex and often intertwined, making it difficult to pinpoint and address specific causes.

Decision-makers in both the RMI and the United States—for example, those who design policy related to immigrant access to services—need information to better understand the factors contributing to current migration and to anticipate possible future impacts of climate change on human migration. A current research project is studying the multiple reasons for Marshallese migration and its effects on migrants themselves and on the communities they are coming from and going to.

Early intervention, occurring already in some places across the region, can prevent costly and lengthy rebuilding of communities and livelihoods and minimize displacement and relocation (see Ch. 28: Adaptation, KM 4). Early intervention includes taking steps now to protect infrastructure, as is being done by the Honolulu Board of Water Supply (see Case Study "Planning for Climate Impacts on Infrastructure"), such as redesigning areas to allow for periodic inundation and flooding, reverting natural areas to facilitate a return to original drainage patterns, and building social networks to take immediate actions and plan future responses.[222] Policymakers prefer approaches that are low cost, yield benefits even in the absence of climate change, are reversible and flexible, and build safety margins into new investments to accommodate uncertain future changes.[196] Examples of safety margins include more climate-adapted housing, provisions to expand rainwater storage capacity in water tanks, reverse osmosis capabilities for removing salt from water (Figure 27.4), development of saline-tolerant crop varieties (Figure 27.13), and implementation of more effective early warning systems for typhoons, king tides, and coastal storms.

Across the region, groups are coming together to minimize damage and disruption from coastal flooding and inundation, as well as other climate-related impacts. In some cases, the focus is on taking preventive measures to remove exposure to hazards, rather than focusing on protection and impact reduction (for example, through relocation or increased protection of threatened infrastructure). On Kosrae, the Federated States of Micronesia, for example, the Kosrae Island Resource Management Authority has laid out a strategy to redirect development inland (such as repositioning the main access road away from the shoreline to higher ground).[7]

Social cohesion is already strong in many communities in the region, making it possible to work together to take action. Stakeholders representing academia, resource managers, and government came together across the State of Hawai'i to summarize ecosystem-specific vulnerabilities and prioritize potential

adaptations at the island scale.[100] In Molokai, a community-led effort is underway to prepare traditional fishponds for climate change (see Case Study "Bridging Climate Science and Traditional Culture"). One of the core benefits of this effort is the strengthening of relationships between the diverse people who will benefit from collaborating to address future climate change impacts on the island.

Where successful, early intervention can lower economic, environmental, social, and cultural costs and reduce or prevent conflict and displacement from ancestral land and resources.

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Opening Image Credit

Honolulu, Hawai‘i: NOAA Teacher at Sea Program, NOAA Ship *Hi‘ialakai*.

Traceable Accounts

To frame this chapter, the regional leads wanted to maximize inclusiveness and represent the key sectoral interests of communities and researchers. To select sectors and a full author team, the coordinating lead author and regional chapter lead author distributed an online Google survey from September to October 2016. The survey received 136 responses representing Hawai'i and all the U.S.-Affiliated Pacific Islands (USAPI) jurisdictions; respondents identified which of the National Climate Assessment (NCA) sectors they were most interested in learning about with respect to climate change in the Pacific Islands and suggested representative case studies.[223] The five top sectors were picked as the focus of the chapter, and a total of eight lead authors with expertise in those sectors were invited to join the regional team. To solicit additional participation from potential technical contributors across the region, two informational webinars spanning convenient time zones across the Pacific were held; 35 people joined in. The webinars outlined the NCA history and process, as well as past regional reports and ways to participate in this Fourth National Climate Assessment (NCA4).

A critical part of outlining the chapter and gathering literature published since the Third National Climate Assessment (NCA3)[224] was done by inviting technical experts in the key sectors to participate in a half-day workshop led by each of the lead authors. A larger workshop centered on adaptation best practices was convened with participants from all sectors, as well as regional decision-makers. In all, 75 participants, including some virtual attendees, took part in the sectoral workshops on March 6 and 13, 2017. Finally, to include public concerns and interests, two town hall discussion events on March 6 and April 19, 2017, were held in Honolulu, Hawai'i, and Tumon, Guam, respectively. Approximately 100 participants attended the town halls. Throughout the refining of the Key Messages and narrative sections, authors met weekly both via conference calls and in person to discuss the chapter and carefully review evidence and findings. Technical contributors were given multiple opportunities to respond to and edit sections. The process was coordinated by the regional chapter lead and coordinating lead authors, as well as the Pacific Islands sustained assessment specialist.

Key Message 1

Threats to Water Supplies

Dependable and safe water supplies for Pacific island communities and ecosystems are threatened by rising temperatures *(very high confidence)*, changing rainfall patterns *(low confidence)*, sea level rise *(very high confidence)*, and increased risk of extreme drought and flooding *(medium confidence)*. Islands are already experiencing saltwater contamination due to sea level rise, which is expected to catastrophically impact food and water security, especially on low-lying atolls *(medium confidence)*. Resilience to future threats relies on active monitoring and management of watersheds and freshwater systems.

Description of evidence base

Vulnerability of water supplies to climate change: With their isolation and limited land areas, Hawai'i and the USAPI are vulnerable to the effects of climate change on water supplies.[72,225] Ongoing and projected changes in temperature and precipitation will have negative effects on water

supplies in Hawai'i and some parts of the USAPI. For example, stream low flow and base flow in Hawai'i decreased significantly over the period 1913–2008, which is at least partly explained by a decline in precipitation.

Temperature change: In Hawai'i, air temperature increased by 0.76°F (0.42°C) over the past 100 years. The year 2015 was the warmest on record at 1.43°F (0.79°C) above the 100-year average. Mean and minimum (nighttime) temperatures both show long-term, statistically significant increasing trends, while the diurnal temperature range (the average difference between daily minimum and maximum temperature) shows a long-term, statistically significant decreasing trend.[59] Estimates of historical temperature changes in Hawai'i are based on the relatively few observing stations with long records and represent the best available data. Further temperature increases in the Hawai'i–USAPI region are highly likely. Northern tropical Pacific (including Micronesia) sea level air temperatures are expected to increase by 2.2°–2.7°F (1.2°–1.5°C) by mid-century and by 2.7°–5.9°F (1.5°–3.3°C) by 2100.[63] Southern tropical Pacific (including American Sāmoa) sea level air temperatures are expected to increase by 1.8°–3.1°F (1.0°–1.7°C) by mid-century and by 2.5°–5.8°F (1.4°–3.2°C) by 2100.[63] Increasing temperatures throughout the Hawai'i–USAPI region might cause increases in potential evapotranspiration,[226] with consequent negative impacts on water supplies.

Precipitation change: While Hawai'i precipitation has experienced upward and downward changes across a range of timescales, more than 90% of the state had a net downward rainfall trend during 1920–2012.[60] Projections of future precipitation changes in Hawai'i are still uncertain. Using a dynamical downscaling approach to project climate changes in Hawai'i for the 20-year period at the end of the this century under a middle-of-the-road scenario (SRES A1B) resulted in increases in mean annual rainfall of up to 30% in the wet windward areas of Hawai'i and Maui Islands and decreases of 40% in some of the dry leeward and high-elevation interior areas.[34] Somewhat different results were obtained using an independent statistical downscaling method.[34] For the lower scenario (RCP4.5), mean annual rainfall in Hawai'i is projected by statistical downscaling to have only small changes in windward areas of Hawai'i and Maui Islands, to decrease by 10%–20% in windward areas of the other islands, and to decrease by up to 60% in leeward areas for the period 2041–2070. For the same scenario, the late-century (2071–2100) projection is similar to the 2041–2070 projection, except that a larger portion of the leeward areas will experience reductions of 20%–60%. For the higher scenario (RCP8.5), windward areas of Hawai'i and Maui Islands will see changes between +10% and –10%, and rainfall in leeward areas will decrease by 10% to more than 60% by the 2041–2070 period. By the late-century period (2071–2100), windward areas of Hawai'i and Maui Islands will see increases of up to 20%, windward areas on other islands will have decreases of 10% to 30%, and leeward areas will have decreases of 10% to more than 60%. The number of climate and water resources monitoring stations has declined across the region,[23,76,77] reducing the ability of researchers to project future changes in climate.

Trends in hydrological extremes in Hawai'i: Increasing trends in extreme 30-day rainfall and the lengths of consecutive dry-day and consecutive wet-day periods[66] indicate that Hawai'i's rainfall is becoming more extreme and suggest that both droughts and floods are becoming more frequent in Hawai'i. With the addition of more years of observed data, and a more detailed spatiotemporal analysis from a grid-box level down to the island level, this contrasts with the earlier findings of a decreasing trend in the number of extreme rainfall events in Hawai'i.[227]

Saltwater contamination due to sea level rise: Sea level rise exacerbates the existing vulnerability of groundwater lenses on small coral islands to contamination by saltwater intrusion by amplifying the impacts of freshwater lens-shrinking droughts and storm-related overwash events.[69]

Major uncertainties

Effects of warming on evapotranspiration: There are uncertainties in how warming will affect cloud cover, solar radiation, humidity, and wind speed. All of these affect potential evapotranspiration and changes in soil moisture, and the effects will differ by region.[228]

Future precipitation changes: Global models differ in their projections of precipitation changes for the Hawai'i–USAPI region.[63] For Hawai'i, downscaled projections differ according to the choice of global model time horizon, emissions scenario, and downscaling method.[229]

Description of confidence and likelihood

There is *very high confidence* in further increases in temperature in the region, based on the consistent results of global climate models showing continued significant increases in temperature in the Hawai'i–USAPI region for all plausible emissions scenarios.

There is *low confidence* regarding projected changes in precipitation patterns, stemming from the divergent results of global models and downscaling approaches and from uncertainties around future emissions. However, for leeward areas of Hawai'i and the eastern part of the Federated States of Micronesia (FSM), future decreases in precipitation are somewhat more likely, based on greater agreement between downscaling approaches for Hawai'i and greater agreement among global models for eastern FSM.

There is *very high confidence* in future increases in sea level, based on widely accepted evidence that warming will increase global sea level, with amplified effects in the low latitudes.

There is *medium confidence* in the increasing risk of both drought and flood extremes patterns, based on both observed changes (for example, increasing lengths of wet and dry periods) and projected effects of warming on extreme weather globally.

There is *medium confidence* in possible future catastrophic impacts on food and water security resulting from saltwater contamination in low atolls due to sea level rise; this is based on *very high confidence* in continuing sea level rise, the known effects of saltwater contamination on water supply and agriculture, and uncertainty regarding the effectiveness of adaptation measures.

Key Message 2

Terrestrial Ecosystems, Ecosystem Services, and Biodiversity

Pacific island ecosystems are notable for the high percentage of species found only in the region, and their biodiversity is both an important cultural resource for island people and a source of economic revenue through tourism (*very high confidence*). Terrestrial habitats and the goods and services they provide are threatened by rising temperatures (*very likely, very high confidence*), changes in rainfall (*likely, medium confidence*), increased storminess (*likely, medium confidence*), and land-use change (*very likely, very high confidence*). These changes promote the spread of invasive species (*likely, low confidence*) and reduce the ability of habitats to support protected species and sustain human communities (*likely, medium confidence*). Some species are expected to become extinct (*likely, medium confidence*) and others to decline to the point of requiring protection and costly management (*likely, high confidence*).

Description of evidence base

Projections of sea level rise have been made at both regional and local scales (see Traceable Account for Key Message 3). Based on these projections, the effects of sea level rise on coastal ecosystems have been evaluated for the Northwest Hawaiian Islands.[18,83,84,86,171,228] There has also been an assessment of the effects of climate change to many small islands across the Pacific Islands region.[70] The effect of sea level rise (and global warming) on mangroves has also been evaluated.[86,230,231,232]

Forecasts of how climate change will affect rainfall and temperature in the main Hawaiian Islands have been based on both statistical and dynamical downscaling of global climate models (GCMs; see Traceable Account for Key Message 1). Statewide vulnerability models have been developed for nearly all species of native plants[233] and forest birds,[43] showing substantial changes in the available habitat for many species. More detailed modeling within Hawai'i Volcanoes National Park has suggested that rare and listed plants being managed in Special Ecological Areas will experience climate changes that make the habitat in these areas unsuitable.[91]

Effects of climate change on streamflow in Hawai'i will largely be driven by changes in rainfall, although geologic conditions affect the discharge of groundwater that provides base flow during dry weather.[234] A regional watershed model from the windward side of Hawai'i Island suggested that control of an invasive tree with high water demand would somewhat mitigate decreases in streamflow that might be caused by a drier climate.[44] Finally, it has been suggested that ocean acidification will decrease the viability of the planktonic larvae of native Hawaiian stream fishes.[99]

Major uncertainties

The timing and magnitude of sea level rise are somewhat uncertain. There is greater uncertainty on how climate change will affect the complex patterns of precipitation over the high islands of Hawai'i. There is also high uncertainty about how plants will respond to changes in their habitats and the extent to which climate change will foster the spread of invasive species.

Description of confidence and likelihood

It is *very likely* that air and water temperatures will increase and that sea level will rise (*very high confidence*). Research indicates that global mean sea level rise will exceed previous estimates and that, in the USAPI, sea level rise is likely to be higher than the global mean (*likely*, *high confidence*). As a result, it is *likely* that climate change will affect low-lying and coastal ecosystems in Hawai'i and other Pacific islands, with *medium confidence* in forecasts of the effects on these ecosystems.

There is *low confidence* as to how rainfall patterns will shift across the main Hawaiian Islands. It is considered *likely* that changes in rainfall will result in ecologic shifts expected to threaten some species. However, there is *low confidence* in specific ecologic forecasts, because the direction and magnitude of rainfall changes are uncertain and there is a lack of robust understanding of how species will respond to those changes. It seems *as likely as not* that the responses of terrestrial biomes and species to climate change will result in additional complexity in the management of rare and threatened species.

Key Message 3

Coastal Communities and Systems

The majority of Pacific island communities are confined to a narrow band of land within a few feet of sea level. Sea level rise is now beginning to threaten critical assets such as ecosystems, cultural sites and practices, economics, housing and energy, transportation, and other forms of infrastructure (*very likely, very high confidence*). By 2100, increases of 1–4 feet in global sea level are very likely, with even higher levels than the global average in the U.S.-Affiliated Pacific Islands (*very likely, high confidence*). This would threaten the food and freshwater supply of Pacific island populations and jeopardize their continued sustainability and resilience (*likely, high confidence*). As sea level rise is projected to accelerate strongly after mid-century, adaptation strategies that are implemented sooner can better prepare communities and infrastructure for the most severe impacts.

Description of evidence base

Multiple lines of research have shown that changes in melting in Greenland,[110] the Antarctic,[107] and among alpine glaciers,[111] as well as the warming of the ocean,[113] have occurred faster than expected. The rate of sea level rise is accelerating,[103] and the early signs of impact are widely documented.[9] Relative to the year 2000, global mean sea level (GMSL) is *very likely* to rise 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1.0–4.3 feet (30–130 cm) by 2100 (*very high confidence* in lower bounds; *medium confidence* in upper bounds for 2030 and 2050; *low confidence* in upper bounds for 2100).[17,105] Future greenhouse gas (GHG) emissions have little effect on projected average sea level rise in the first half of the century, but they significantly affect projections for the second half of the century. Emerging science regarding Antarctic ice sheet stability suggests that, for high emission scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed. Regardless of pathway, it is extremely likely that GMSL rise will continue beyond 2100 (*high confidence*).[105]

Changes in precipitation,[235] Pacific sea level,[4] climate variability,[3] and the unsustainable practices of many human communities among Pacific islands[127] all converge to increase the vulnerability of coastal populations[135] as climate change continues in the future.[55] As sea level rises and average atmospheric temperature continues to increase, wave events[37] associated with changing weather patterns[140] constitute a growing mechanism for delivering[12] damaging saltwater into island aquifer systems,[13] ecosystems,[129] and human infrastructure systems.[17]

In Hawai'i, studies by the Hawai'i Climate Change Mitigation and Adaptation Commission[42] reveal that with 3.2 feet of sea level rise, over 25,800 acres of land in the state would be rendered unusable. Some of that land would erode into the ocean, some would become submerged by inches or feet of standing water, and some areas would be dry most of the year but repeatedly washed over by seasonal high waves. Statewide, about 34% of that potentially lost land is designated for urban use, 25% is designated for agricultural use, and 40% is designated for conservation. The loss of urban land is expected to increase pressure on the development of inland areas, including those designated as agricultural and conservation lands. Across the state, over 6,500 structures located near the shoreline would be compromised or lost with 3.2 feet of sea level rise. Some of these vulnerable structures include houses and apartment buildings, and their loss would result in over 20,000 displaced residents in need of new homes. The value of projected flooded structures, combined with the land value of the 25,800 acres projected to be flooded, amounts to over $19 billion across the state (in 2013 dollars; $19.6 billion in 2015 dollars). However, this figure does not encompass the full loss potential in the state, as monetary losses that would occur from the chronic flooding of roads, utilities, and other public infrastructure were not analyzed in this report and are expected to amount to as much as an order of magnitude greater than the potential economic losses from land and structures. For example, over 38 miles of major roads would be chronically flooded across the state with 3.2 feet of sea level rise. Utilities, such as water, wastewater, and electrical systems, often run parallel and underneath roadways, making lost road mileage a good indication of the extent of lost utilities. This chronic flooding of infrastructure would have significant impacts on local communities as well as reverberating effects around each island.

The loss of valuable natural and cultural resources across all islands would cost the state dearly, due to their intrinsic value. Beaches that provide for recreation, wildlife habitat, and cultural tradition would erode, from iconic sites such as Sunset Beach on O'ahu to neighborhood beach access points rarely visited by anyone except local residents. Some beaches would be lost entirely if their landward migration is blocked by roads, structures, shoreline armoring, or geology. The flooding of the more than 2,000 on-site sewage disposal systems with 3.2 feet of sea level rise would result in diminished water quality in streams and at beaches and shoreline recreation areas. The loss of and harm to native species and entire ecosystems would have implications for Hawaiian cultural traditions and practices, which are closely tied to the natural environment. Further, nearly 550 cultural sites in the state would be flooded, and many Hawaiian Home Lands communities would be impacted by flooding. In some cases, inland migration or careful relocation of these natural and cultural resources is expected to be possible. In other cases, the resources are inextricably bound to place and would be permanently altered by flooding.[42]

Marra and Kruk (2017)[142] describe climate trends for the USAPI. Globally and locally, observations of GHG concentrations, surface air temperatures, sea level, sea surface temperature, and ocean acidification show rising trends at an increasing rate. Trends in measures of rainfall, surface

winds, and tropical cyclones are not as readily apparent. Patterns of climate variability characterize these measures and tend to mask long-term trends. A lack of high-quality, long-term observational records, particularly with respect to in situ stations, contributes to difficulties in discerning trends. To maintain and enhance our ability to assess environmental change, attention needs to be given to robust and sustained monitoring.

There are consistent subregional changes in the number of days with high winds. The global frequency of tropical cyclones (TCs) appears to be showing a slow downward trend since the early 1970s. In the Pacific region, long-term TC trends in frequency and intensity are relatively flat, with the record punctuated by as many active as inactive years.[142]

Major uncertainties

Major uncertainties lie in understanding and projecting the future melting behavior of the Antarctic and Greenland ice sheets. To date, new observations attest to melting occurring at higher than expected rates. If this continues to be the case, it is plausible for future sea level rise to exceed even worst-case scenarios. Secondary feedbacks to warming, such as changes in the global thermohaline circulation; shifts in major weather elements, such as the intertropical convergence zone and the polar jet stream; and unexpected modes of heat distribution across the hemispheres risk complex responses in the climate system that are not well understood. Pacific climate variability is a governing element that amplifies many aspects of climate change, such as drought, sea level, storminess, and ocean warming. A number of mechanisms through which climate change might alter Pacific variability have been proposed on the basis of physical modeling, but our understanding of the variability remains low, and confidence in projected changes is also low. For instance, in any given Pacific region, our understanding of future TC occurrence, intensity, and frequency is low. Future physical responses to climate change that have not yet been described are possible. These uncertainties greatly limit our ability to identify the chronology of changes to expect in the future.

Description of confidence and likelihood

There is *very high confidence* that a continued rise in global temperature will lead to increases in the rate of sea level rise. There is less confidence in the projected amounts of sea level rise during this century, and there is *low confidence* in the upper bounds of sea level rise by the end of the century. Sea level rise will *very likely* lead to saltwater intrusion, coastal erosion, and wave flooding. It is *very likely* this will strain the sustainability of human infrastructure systems, limit freshwater resources, and challenge food availability. If the high-end projections of future sea level rise materialize, it is *very likely* this will threaten the very existence of Pacific island coastal communities.

Key Message 4

Oceans and Marine Resources

Fisheries, coral reefs, and the livelihoods they support are threatened by higher ocean temperatures and ocean acidification (*very likely, high confidence*).Widespread coral reef bleaching and mortality have been occurring more frequently, and by mid-century these events are projected to occur annually, especially if current trends in emissions continue (*likely, medium confidence*). Bleaching and acidification will result in loss of reef structure, leading to lower fisheries yields, and loss of coastal protection and habitat (*very likely, very high confidence*). Declines in oceanic fishery productivity of up to 15% and 50% of current levels are projected by mid-century and 2100, respectively, under the higher scenario (RCP8.5; *likely, medium confidence*).

Description of evidence base

The Key Message was developed based on input from an expert working group convened at the outset of this section development and supported by extensive literature.

Ocean warming: NCA3 documented historical increases in sea surface temperature (SST), and current levels in much of the region have now exceeded the upper range of background natural variation.[32,154] Future increases are projected even under lower-than-current emissions rates.[123,154]

Ocean acidification: Atmospheric carbon dioxide levels recorded at Mauna Loa, Hawai'i, have recently exceeded 400 parts per million, and oceanic pH levels measured off O'ahu have steadily declined from an annual average of about 8.11 to 8.07 over the past 25 years (data from Hawai'i Ocean Time Series, SOEST, University of Hawai'i) and are projected to decrease to 7.8 by 2100.[123] As pH declines, it lowers the saturation level of aragonite (the form of calcium carbonate used by corals and many other marine organisms), reducing coral and shell growth.[125] By the end of the century, aragonite saturation is projected to decline from a current level of 3.9 to 2.4, representing extremely marginal conditions for coral reef growth.[32,123,159,161]

Bleaching events: These continue to occur—most recently over successive years—with widespread impacts.[45,158] Sea surface temperature time series from a suite of Climate Model Intercomparison Project 5 outputs that are statistically downscaled to 4 km resolution are used to project the year when coral reefs will begin to experience annual bleaching under the higher scenario (RCP8.5).[46] These data forecast that bleaching will be an annual event for the region starting in about 2035.[46]

Mortality: During the 2014–2015 bleaching events, coral mortality in western Hawai'i was estimated at 50%[45] and over 90% at the pristine equatorial Jarvis Atoll.[156]

Coral reef ecosystem impacts: Coral reef cover around the Pacific Islands region is projected to decline from the current average level of about 40% to 15%–30% by 2035 and 10%–20% by 2050.[123] The loss of coral reef habitat is projected to reduce fish abundance and fisheries yields by 20%.[123] Loss of coral reefs will result in increased coastal erosion.[23,236] Tourism is the major economic engine in Hawai'i, and healthy coral reef ecosystems are critical to this economy. Under the higher scenario (RCP8.5), coral reef loss is projected to result in a total economic loss of $1.3 billion per

year in 2050 and $1.9 billion per year in 2090 (in 2015 dollars, undiscounted). In 2090, a lower scenario (RCP4.5) would avoid 16% of coral cover loss and $470 million per year (in 2015 dollars, undiscounted) compared to the higher scenario.[162] The confidence intervals around these loss estimates under RCP8.5 for 2050 range from a gain of $240 million to a loss of $1.9 billion, and for 2090 range from a loss of $1.7 billion to $1.9 billion (in 2015 dollars, undiscounted).[162]

Insular fisheries: Insular fishes, including both coral reef fishes and more mobile, coastal pelagics (species such as mahi mahi and wahoo), are impacted both from declines in carrying capacity and loss from migration in response to temperature change. Taken together, declines in maximum catch potential exceeding 50% from late 20th century levels under the higher scenario are projected by 2100 for the exclusive economic zones of most islands in the central and western Pacific.[163]

Oceanic fisheries: A number of studies have projected that ocean warming will result in lower primary productivity due to increased vertical stratification and loss of biodiversity as organisms move poleward.[129,167,169] Estimates of up to a 50% decline in fisheries yields are projected with two different modeling approaches.[129,169] The impact of climate change specifically on fisheries targeting bigeye, yellowfin, and skipjack tunas in the western and central equatorial Pacific has been explored with fisheries models.[123,237,238] However, there is considerable uncertainty in the projections of population trends, given our lack of understanding of how the various life stages of these species will respond and the sensitivity of the projections to the specific model used.[238,239]

Major uncertainties

A major uncertainty for coral reefs is whether they can evolve rapidly enough to keep up with the changing temperature and pH.[164,165] In the oceanic ecosystem, the impacts of changing ocean chemistry on the entire food web are not well understood but are expected to result in shifts in the composition of the species or functional groups, altering the energy flow to top trophic levels.[240,241] For example, a shift in the micronekton community composition (squids, jellyfishes, fishes, and crustaceans) was projected to alter the abundance of food available to fishes at the top of the food web.[240] The impact of climate change on the intensity and frequency of interannual and decadal modes of climate variability (such as El Niño–Southern Oscillation and Pacific Decadal Oscillation) is not well known but has very important consequences.[1]

Description of confidence and likelihood

There is *high confidence* that fisheries and the livelihoods they support are threatened by warmer ocean temperatures and ocean acidification. Widespread and multiyear coral reef bleaching and mortality are already occurring. It is *likely*, based on modeled SST projections, that by mid-century, bleaching will occur annually with associated mortality.

There is *medium confidence* in the projection of annual bleaching by mid-century, as it does not take into account any adaptation in corals.

There is *high confidence* that bleaching and rising seawater acidity will result in loss of reef structure, leading to lower fisheries yields and loss of coastal protection. This is deemed *very likely* because significant coral mortality has recently been observed in western Hawaiian coral reefs that suffered from the 2015 bleaching event. Further, the positive relationship between fish

density and coral reef cover is well established. The magnitude of this impact depends on the extent that coral species exhibit adaptive or resilience capacity.

There is *medium confidence* that declines in oceanic fishery productivity of up to 15% and 50% are likely by mid-century and 2100, respectively. These declines are considered *likely* because we have seen related linkages between climate variability such as ENSO and the Pacific Decadal Oscillation and fisheries yields that provide an analog in some ways to global warming impacts. The uncertainty lies in our limited understanding of the linkages and feedbacks in the very complex oceanic food web. As temperate habitats warm, they will likely gain some tropical species, while the tropical habitats will likely only lose species.

Key Message 5

Indigenous Communities and Knowledge

Indigenous peoples of the Pacific are threatened by rising sea levels, diminishing future freshwater availability, and shifting ecosystem services. These changes imperil communities' health, well-being, and modern livelihoods, as well as their familial relationships with lands, territories, and resources (*likely, high confidence*). Built on observations of climatic changes over time, the transmission and protection of traditional knowledge and practices, especially via the central role played by Indigenous women, are intergenerational, place-based, localized, and vital for ongoing adaptation and survival.

Description of evidence base

The research supporting this Key Message examines the impacts of climate change on the lands, territories, and resources of the Pacific region and its Indigenous communities.

It is foundational to highlight the interconnectedness and important familial relationship Indigenous peoples have with their lands, territories, and resources. Native Hawaiian attorneys and professors Sproat and Akutagawa discuss the health impacts and threats that climate change poses for Indigenous communities and their relationship with ancestral resources. Sproat states that "any such loss will result in the loss of culture."[177] Further support is found in a community health assessment done by Akutagawa and others that states, "In traditional Hawaiian conceptions of health, personal harmony and well-being are deemed to stem from one's relationship with the land, sea, and spiritual world."[176]

Governments and their support institutions are also sharing outcomes of projects they've initiated over the years that document not only the successes but also the challenges, observations, and lessons learned.[149,179] This includes the recognition of the dominant role of Indigenous women in island communities as gatherers and in household activities; economic development activities like transporting and selling produce;[146] distribution of crops;[179] maintenance of crop diversity, food security, security of income, seed saving, and propagation; transmission of traditional knowledge and practices, especially spiritual practices;[185] and stewarding underwater reef patches and stone enclosures as gardens.[242]

In writing this Key Message, the authors considered the body of research focusing on the impacts of climate change on Pacific communities such as sea level rise,[104,115,147,177,243] ocean acidification,[84,115,147,177,184] and drought.[147,177,179,184,242,243,244] Clear examples used in the studies illustrate the confidence that Indigenous communities are at high risk for experiencing effects at a physical,[176,245] social,[22,175,176,177,184,244] and spiritual level.[21,84,174,175,176,177,245]

There is very strong evidence that traditional knowledge is key to the resilience and adaptive capacity of Indigenous peoples of the Pacific.[21,84,176,180,184,185,242]

Major uncertainties

There is no doubt that Indigenous communities of the Pacific are being impacted by climate change. However, the rate and degree of the impacts on the spiritual, relational, and ancestral connectedness vary from community to community and on the type of practice being impacted. This variable is difficult to document and express in certain circumstances. Additionally, the degree of the impact varies according to the livelihoods of the community and the specific climatic and socioeconomic and political circumstances of the island in question.

Description of confidence and likelihood

There is *high confidence* that climate change is having far-reaching effects on the land security, livelihood security, habitat security, and cultural food security of Indigenous peoples of the Pacific.

It is *likely* that most of these impacts will have negative effects on the cultural heritage of the Pacific island communities.

There is *high confidence* that traditional knowledge together with science will support the adaptive capacity of Pacific island communities to survive on their islands.

Key Message 6

Cumulative Impacts and Adaptation

Climate change impacts in the Pacific Islands are expected to amplify existing risks and lead to compounding economic, environmental, social, and cultural costs (*likely, medium confidence*). In some locations, climate change impacts on ecological and social systems are projected to result in severe disruptions to livelihoods (*likely, high confidence*) that increase the risk of human conflict or compel the need for migration. Early interventions, already occurring in some places across the region, can prevent costly and lengthy rebuilding of communities and livelihoods and minimize displacement and relocation (*likely, high confidence*).

Description of evidence base

For Atlantic and eastern North Pacific hurricanes and western North Pacific typhoons, increases are projected in precipitation rates and intensity. The frequency of the most intense of these storms is projected to increase in the western North Pacific and in the eastern North Pacific (see also Key Message 3).[246] Studies indicate that Hawai'i will see an increased frequency of tropical cyclones (TCs) due to storm tracks shifting northward in the central North Pacific.[40,247]

The *Climate Science Special Report* (CSSR) summarizes extensive evidence that is documented in the climate science literature and is similar to statements made in NCA3 and international[106] assessments.[33] More recent downscaling studies have further supported these assessments,[248] though pointing out that the changes (future increased intensity and TC precipitation rates) will not necessarily occur in all basins.[246]

Damage from TCs is significant. Tropical Cyclone Evan struck Sāmoa in December 2012 and caused damage and losses of approximately $210 million dollars (dollar year not reported), representing 30% of its annual gross domestic product (GDP). Tropical Cyclone Pam struck Vanuatu, Tuvalu, and Kiribati in 2015; in Vanuatu, it killed 11 people and caused approximately $450 million (dollar year not reported) in damages and losses, equal to 64% of GDP.[196]

In the CSSR, future relative sea level rise as shown for the 3.3-feet (1 m) Interagency scenario in 2100 indicates that, because they are far from all glaciers and ice sheets, relative sea level rise in Hawai'i and other Pacific islands due to any source of melting land ice is amplified by the static-equilibrium effects. Static-equilibrium effects on sea level are produced by the gravitational, elastic, and rotational effects of mass redistribution resulting from ice loss.[105]

Sea level rise across Hawai'i is projected to rise another 1–3 feet by the end of this century. Sea level rise has caused an increase in high tide floods associated with nuisance-level impacts. High tide floods are events in which water levels exceed the local threshold (set by the National Oceanic and Atmospheric Administration's National Weather Service) for minor impacts. These events can damage infrastructure, cause road closures, and overwhelm storm drains. Along the Hawaiian coastline, the number of tidal flood days (all days exceeding the nuisance-level threshold) has also increased, with the greatest number occurring in 2002–2003. Continued sea level rise will present major challenges to Hawai'i's coastline through coastal inundation and erosion. Seventy percent of Hawai'i's beaches have already been eroded over the past century, with more than 13 miles of beach completely lost. Sea level rise will also affect Hawai'i's coastal storm water and wastewater management systems and is expected to cause extensive economic impacts through ecosystem damage and losses in property, tourism, and agriculture.[247]

In the Pacific Islands region, population, urban centers, and critical infrastructure are concentrated along the coasts. This results in significant damages during inundation events. In December 2008, wind waves generated by extratropical cyclones, exacerbated by sea level rise, caused a series of inundation events in five Pacific island nations.[9] An area of approximately 3,000 km in diameter was affected, impacting approximately 100,000 people. Across the islands, major infrastructure damage and crop destruction resulted, costing millions of dollars and impacting livelihoods, food security, and freshwater resources.

The increases in the frequency and intensity of climate change hazards, including cyclones, wind, rainfall, and flooding, pose an immediate danger to the Pacific Islands region. A decrease in the return times of extreme events, which will reduce the ability of systems to recover, will likely cause long-term declines in welfare.[181] For small islands states, the damage costs of sea level rise are large in relation to the size of their economies.[194,195]

The social science research on climate and conflict suggests a possible association between climate variability and change and conflict. Consensus or conclusive evidence of a causal link

remains elusive. Hsiang et al. (2013)[249] find strong causal evidence linking climatic events to human conflict across a range of spatial scales and time periods and across all major regions of the world. They further demonstrate that the magnitude of climate influence is substantial.[249] Specifically, large deviations from average precipitation and mild temperatures systematically increase the risk of many types of conflict (intergroup to interpersonal), often substantially. Hsiang and Burke (2014)[250] describe their detailed meta-analysis, examining 50 rigorous quantitative studies, and find consistent support for a causal association between climatological changes and various conflict outcomes.[250] They note, however, that multiple mechanisms can explain this association and that the literature is currently unable to decisively exclude any proposed pathway between climatic change and human conflict.[249]

Evidence of the impact of climate on livelihoods is also well established. Barnett and Adger (2003, 2007)[191,197] are among a range of studies that conclude that climate change poses risks to livelihoods, communities, and cultures.[197] These risks can influence human migration. The United Nations Environment Programme finds that the degree to which climatic stressors affect decisions to migrate depend on a household's vulnerability and sensitivity to climatic factors.[206]

Major uncertainties

A key uncertainty remains the lack of a supporting, detectable anthropogenic signal in the historical data to add further confidence to some regional projections. As such, confidence in the projections is based on agreement among different modeling studies. Additional uncertainty stems from uncertainty in both the projected pattern and magnitude of future sea surface temperatures.[33,40,248]

One study projects an increase in tropical cyclone frequency (TCF) of occurrence around the Hawaiian Islands but stipulates that TCF around the Hawaiian Islands is still very low in a warmed climate, so that a quantitative evaluation of the future change involves significant uncertainties.[40]

Uncertainties in reconstructed global mean sea level (GMSL) change relate to the sparsity of tide gauge records, particularly before the middle of the twentieth century, and to the use of a variety of statistical approaches to estimate GMSL change from these sparse records. Uncertainties in reconstructed GMSL change before the 20th century also relate to the lack of geological proxies (preserved physical characteristics of the past environment that can stand in for direct measurement) for sea level change, the interpretation of these proxies, and the dating of these proxies. Uncertainty in attribution relates to the reconstruction of past changes and the magnitude of natural variability in the climate.

Since NCA3, multiple approaches have been used to generate probabilistic projections of GMSL rise. These approaches are in general agreement. However, emerging results indicate that marine portions of the Antarctic ice sheet are more unstable than previously thought. The rate of ice sheet mass changes remains challenging to project.

In sea level rise projections, Antarctic contributions are amplified along U.S. coastlines, while Greenland contributions are dampened; regional sea level is projected to be higher than if driven by a more extreme Greenland contribution and a somewhat less extreme Antarctic contribution.[17]

The degree to which climate variability and change impact conflict, and related causal pathways, remains uncertain. This is compounded by the fact that different types of conflict—social, political,

civil, or violent—are conflated.[209,251] Violent conflict can describe interpersonal-, intergroup-, and international-level disputes. Some researchers contend that systematic research on climate change and armed conflict has not revealed a direct connection.[252] Gemenne et al. (2014)[208] argue that there is a lack of convincing empirical evidence or theories that explain the causal connection between climate change and security. They do, however, note that there is some evidence for statistical correlation between climatic changes and conflict, broadly referenced.

Gemenne et al. (2014)[208] also note that the relationship between climate change and security comes from observation of past patterns and that present and projected climate change have no historical precedent. In effect, understanding past crises and adaptation strategies will no longer be able to help us understand future crises in a time of significant climate change.

The degree to which climate variability and change affect migration decisions made today also remains uncertain. This is in part due to the diverse scenarios that comprise climate migration, which themselves result from multiple drivers of migration.[251] Burrows and Kinney (2016)[251] detail examples of climate extremes leading to migration conflicts since 2000, yet they note that there are surprisingly few case studies on recent climate extremes that lead to migration and conflict specifically, despite an increasing body of literature on the theory.

While researchers disagree as to the degree to which climate change drives conflict and migration and the causal pathways that connect them, there is agreement that further research is needed. Buhaug (2015)[252] and Gemenne et al. (2014)[208] argue for research to develop a more refined theoretical understanding of possible indirect and conditional causal connections between climate change and, specifically, violent conflict.[252] Hsiang and Burke (2014)[250] would like additional research that reduces the number of competing hypotheses that attempt to explain the overwhelming evidence that climatic variables are one of many important causal factors in human conflict.[250] Burrows and Kinney (2016)[251] explore the potential pathways linking climate change, migration, and increased risk of conflict and argue that future research should focus on other pathways by which climate variability and change are related to conflict, in addition to the climate–migration–conflict pathway. Kallis and Zografos (2014)[209] seek greater understanding of the potential harm of certain climate change adaptation measures that have the potential to result in maladaptation by spurring conflict.

Description of confidence and likelihood

There is *medium confidence* that climate change will yield compounding economic, environmental, social, and cultural costs. There is greater evidence of these compounding costs resulting from extreme events that are exacerbated by climate change.

There is *high confidence* that food and water insecurity will result in severe disruptions to livelihoods, including the displacement and relocation of island communities.

It is *likely* that the absence of interventions will result in the costly and lengthy rebuilding of communities and livelihoods and more displacement and relocation. Events have played out repeatedly across the region and have resulted in damage, disruptions, and displacements.

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28 Reducing Risks Through Adaptation Actions

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28 Reducing Risks Through Adaptation Actions

Seawall surrounding Kivalina, Alaska

Key Message 1

Adaptation Implementation Is Increasing

Adaptation planning and implementation activities are occurring across the United States in the public, private, and nonprofit sectors. Since the Third National Climate Assessment, implementation has increased but is not yet commonplace.

Key Message 2

Climate Change Outpaces Adaptation Planning

Successful adaptation has been hindered by the assumption that climate conditions are and will be similar to those in the past. Incorporating information on current and future climate conditions into design guidelines, standards, policies, and practices would reduce risk and adverse impacts.

Key Message 3

Adaptation Entails Iterative Risk Management

Adaptation entails a continuing risk management process; it does not have an end point. With this approach, individuals and organizations of all types assess risks and vulnerabilities from climate and other drivers of change (such as economic, environmental, and societal), take actions to reduce those risks, and learn over time.

Key Message 4

Benefits of Proactive Adaptation Exceed Costs

Proactive adaptation initiatives—including changes to policies, business operations, capital investments, and other steps—yield benefits in excess of their costs in the near term, as well as over the long term. Evaluating adaptation strategies involves consideration of equity, justice, cultural heritage, the environment, health, and national security.

Key Message 5

New Approaches Can Further Reduce Risk

Integrating climate considerations into existing organizational and sectoral policies and practices provides adaptation benefits. Further reduction of the risks from climate change can be achieved by new approaches that create conditions for altering regulatory and policy environments, cultural and community resources, economic and financial systems, technology applications, and ecosystems.

Executive Summary

Across the United States, many regions and sectors are already experiencing the direct effects of climate change. For these communities, climate impacts—from extreme storms made worse by sea level rise, to longer-lasting and more extreme heat waves, to increased numbers of wildfires and floods—are an immediate threat, not a far-off possibility. Because these impacts are expected to increase over time, communities throughout the United States face the challenge not only of reducing greenhouse gas emissions, but also of adapting to current and future climate change to help mitigate climate risks.

Adaptation takes place at many levels—national and regional but mainly local—as governments, businesses, communities, and individuals respond to today's altered climate conditions and prepare for future change based on the specific climate impacts relevant to their geography and vulnerability. Adaptation has five general stages: awareness, assessment, planning, implementation, and monitoring and evaluation. These phases naturally build on one another, though they are often not executed sequentially and the terminology may vary. The Third National Climate Assessment (released in 2014) found the first three phases underway throughout the United States but limited in terms of on-the-ground implementation. Since then, the scale and scope of adaptation implementation have increased, but in general, adaptation implementation is not yet commonplace.

One important aspect of adaptation is the ability to anticipate future climate impacts and plan accordingly. Public- and private-sector decision-makers have traditionally made plans assuming that the current and future climate in their location will resemble that of the recent past. This assumption is no longer reliably true. Increasingly, planners, builders, engineers, architects, contractors, developers, and other individuals are recognizing the need to take current and projected climate conditions into account in their decisions about the location and design of buildings and infrastructure, engineering standards, insurance rates, property values, land-use plans, disaster response preparations, supply chains, and cropland and forest management.

In anticipating and planning for climate change, decision-makers practice a form of risk assessment known as iterative risk management. Iterative risk management emphasizes that the process of anticipating and responding to climate change does not constitute a single set of judgments at any point in time; rather, it is an ongoing cycle of assessment, action, reassessment, learning, and response. In the adaptation context, public- and private-sector actors manage climate risk using three types of actions: reducing exposure, reducing sensitivity, and increasing adaptive capacity.

Climate risk management includes some attributes and tactics that are familiar to most businesses and local governments, since these organizations already commonly manage or design for a variety of weather-related risks, including coastal and inland storms, heat waves, water availability threats, droughts, and floods. However, successful adaptation also requires the often unfamiliar challenge of using information on current and future climate, rather than past climate, which can prove difficult for those lacking experience with climate change datasets and concepts. In addition, many professional practices and guidelines, as well as legal requirements, still call for the use of data based on past climate. Finally, factors such as access to resources, culture, governance, and available information can affect not only the risk faced by different populations but also the best ways to reduce their risks.

Achieving the benefits of adaptation can require up-front investments to achieve longer-term savings, engaging with differing stakeholder interests and values, and planning in the face of uncertainty. But adaptation also presents challenges, including difficulties in obtaining the necessary funds, insufficient information and relevant expertise, and jurisdictional mismatches.

In general, adaptation can generate significant benefits in excess of its costs. Benefit–cost analysis can help guide organizations toward actions that most efficiently reduce risks, in particular those that, if not addressed, could prove extremely costly in the future. Beyond those attributes explicitly measured by benefit–cost analysis, effective adaptation can also enhance social welfare in many ways that can be difficult to quantify and that people will value differently, including improving economic opportunity, health, equity, security, education, social connectivity, and sense of place, as well as safeguarding cultural resources and practices and environmental quality.

A significant portion of climate risk can be addressed by mainstreaming; that is, integrating climate adaptation into existing organizational and sectoral investments, policies, and practices, such as planning, budgeting, policy development, and operations and maintenance. Mainstreaming of climate adaptation into existing decision processes has already begun in many areas, such as financial risk reporting, capital investment planning, engineering standards, military planning, and disaster risk management. Further reduction of the risks from climate change, in particular those that arise from futures with high levels of greenhouse gas emissions, calls for new approaches that create conditions for altering regulatory and policy environments, cultural and community resources, economic and financial systems, technology applications, and ecosystems.

Five Adaptation Stages and Progress

The figure illustrates the adaptation iterative risk management process. The gray arced lines compare the current status of implementing this process with the status reported by the Third National Climate Assessment in 2014. Darker color indicates more activity. *From Figure 18.1* (*Source: adapted from National Research Council, 2010.*[1] *Used with permission from the National Academies Press, ©2010, National Academy of Sciences*).

Introduction

Many regions and sectors across the United States already experience significant impacts from climate change effects, and many of these effects are projected to increase. By the middle of this century, annual losses in the United States due to climate change could reach hundreds of billions of dollars (Ch. 29: Mitigation).[2]

Adaptation refers to actions taken at the individual, local, regional, and national levels to reduce risks from even today's changed climate conditions and to prepare for impacts from additional changes projected for the future.[3,4,5,6]

Adaptation is a form of risk management. Risk is sometimes defined as the likelihood of an event's occurrence multiplied by a measure of its consequences for human and natural systems. But because the probabilities and consequences of climate change threats are often not known with precision, and because different people often value the same consequences differently, it is useful to define risk more broadly as "the potential for adverse consequences when something of value is at stake, and the outcome is uncertain."[7] Risk arises from the combination of exposure to climate hazards, sensitivity to those hazards, and adaptive capacity. Adaptation can, however, provide significant societal benefits, reducing by more than half the cost of climate impacts in some sectors (Ch. 29: Mitigation).[8]

Adaptation involves managing both short- and long-term risks. Many important climate-influenced effects—storm intensity, sea level, frequency of heat waves—have already changed due to past greenhouse gas (GHG) emissions and will continue to change in the decades ahead.[3,4] Because several GHGs, in particular carbon dioxide, reside in the atmosphere for decades or longer, many climate-influenced effects are projected to continue changing through 2050, even if GHG emissions were to stop immediately. Thus, climate risk management requires adaptation for the next several decades, independent of the extent of GHG emission reductions. After 2050, the magnitude of changes, and thus the demands on adaptation, begins to depend strongly on the scale of GHG emissions reduction today and over the coming decades.[4,9]

Individuals, business entities, governments, and civil society as a whole can take adaptation actions at many different scales. Some of these are changes to business operations, adjustments to natural and cultural resource management strategies, targeted capital investments across diverse sectors, and changes to land use and other policies. Adaptation actions can yield beneficial short-term and/or longer-term outcomes in excess of their costs, based on economic returns, ecological benefits, and broader concepts of social welfare and security. Moreover, many strategies can provide multiple benefits, resulting in long-term cost savings. For example, restoring wetlands can provide valuable habitat for fish and wildlife as well as flood protection to nearby communities,[10] and conserving mangrove ecosystems can protect coastal communities from damaging storms[11] as well as help to store carbon.[12]

People are not uniformly vulnerable to climate change. Access to resources, culture, governance, and information affects the risks faced by different populations and partly determines the best ways to reduce their risks.[13] Achieving the benefits of adaptation can require up-front investments to achieve longer-term savings, engaging with differing stakeholder interests and values, and planning in the face of uncertainty.

Integrating climate risk management into existing design, planning, and operations

workflows (or mainstreaming), in contrast to adding novel decision processes for climate adaptation alone, can provide many adaptation benefits.[14,15,16] Additional climate risk reduction, particularly under the most severe longer-term climate change projections, emphasizes the need for more and more significant changes to regulatory and policy environments at all scales, to cultural and community resource planning, to economic and financial systems, to technology applications, and to ecosystems.

Key Message 1

Adaptation Implementation Is Increasing

Adaptation planning and implementation activities are occurring across the United States in the public, private, and non-profit sectors. Since the Third National Climate Assessment, implementation has increased but is not yet commonplace.

Adaptation has five general stages: 1) awareness, 2) assessment, 3) planning, 4) implementation, and 5) monitoring and evaluation, as shown in Figure 28.1,[17,18] although these are also known by other terms (see, for example, the U.S. Climate Resilience Toolkit at https://toolkit.climate.gov/ and the University of Notre Dame's Collaboratory for Adaptation to Climate Change at http://gain.nd.edu). Adaptation is an ongoing process in which organizations and individuals repeatedly cycle through the process shown in Figure 28.1, though specific adaptation efforts can follow different routes through these stages (e.g., California Emergency Planning Agency and California Natural Resources Agency 2012[19]).

The Third National Climate Assessment (NCA3) found that the first three stages were underway throughout the United States but with limited on-the-ground implementation.[18] Since then, the scale and scope of adaptation implementation have increased, including by federal, state, tribal, and local agencies (see Vogel et al. 2017, Halofsky et al. 2015, Leggett 2015, Ray and Grannis 2015, Wentz 2017, and the many examples of adaptation implementation in this chapter and elsewhere in this report[14,20,21,22,23]). For instance, Miami-Dade County's Capital Improvement Program is addressing hazards related to sea level rise, as is San Francisco's 2015 Seawall Resiliency Project. It remains difficult, however, to tally the extent of adaptation implementation in the United States because there are no common reporting systems, and many actions that reduce climate risk are not labeled as climate adaptation.[14] Enough is known, however, to conclude that adaptation implementation is not uniform nor yet common across the United States.[24]

Adaptation actions in the United States have increased in part due to 1) the growing awareness of climate-related threats and impacts and the risks these pose to business operations and supply chains (Ch. 16: International, KM 1), critical public infrastructure and communities, natural areas and public lands, and ecosystems; 2) the wider recognition that investing in adaptation provides economic and social benefits that exceed the costs; and 3) the increasing number and magnitude of extreme events that have occurred.[14]

Figure 28.1: The figure illustrates the adaptation iterative risk management process. The gray arced lines compare the current status of implementing this process with the status reported by the Third National Climate Assessment in 2014. Darker color indicates more activity. Source: adapted from National Research Council, 2010.[1] Used with permission from the National Academies Press, ©2010, National Academy of Sciences.

Box 28.1: Department of Housing and Urban Development National Disaster Resilience Competition

Rebuild by Design is a design-driven approach to create innovative local resilience solutions conducted in the aftermath of Superstorm Sandy (http://www.rebuildbydesign.org/about#comp456). It was structured to connect local communities with some of the Nation's leading design firms to identify and solve problems collaboratively and to address vulnerabilities exposed by Superstorm Sandy. The design solutions for the winning proposals ranged in scope and scale from large-scale green infrastructure projects to small-scale residential resilience retrofits. The competition process strengthened the understanding of regional interdependencies, fostering coordination and resilience both at the local level and across the United States. Ultimately, nine projects were selected for implementation and received Community Development Block Grant-Disaster Recovery funding totaling $930 million.

While the level of implementation is now higher than at the time of NCA3, the scale of adaptation implementation for some effects and locations seems incommensurate with the projected scale of climate threats.[25] Communities have focused more on actions that address current variability and recent extreme events than on actions to prepare for future change and emergent threats.[14] Communities are currently focused more on capacity building and on making buildings and other assets less sensitive to climate impacts. Communities have been less focused on reducing exposure through actions such as land-use change (preventing building in high-risk locations) and retreat. Furthermore, many communities' adaptation actions arise and are funded in the context of recovery after an event, rather than taken proactively. Often, such adaptation is not as comprehensive as suggested by best practice guidance, as when adaptation plans address sea level rise but not other climate impacts. Few current adaptation plans seek to exploit synergies among various types of actions, and many plans pay little attention to the costs of actions or their co-benefits. Often explicit attention to evaluation and monitoring is scant or nonexistent.

Managing the Challenge

Public- and private-sector decision-makers have traditionally made plans assuming that the current and future climate will resemble the recent past, an assumption known as stationarity.[27] The assumption is often made explicitly. For instance, in order to design a new dam or to negotiate contracts on future deliveries of hydropower and irrigation water, a water agency might use probability distributions for precipitation and extreme flow events that are based on past or current streamflows in a watershed. In other cases, this assumption is made implicitly, as when a city issues building permits for coastal properties using current flood maps without updating them to reflect projected sea level rise.

Box 28.2: Adaptation Actions by Individuals

Many jurisdictions publish guidance to help individuals take actions to reduce the risks from natural hazards. For example, the city of Chicago suggests residents in flood-prone areas take the following actions **before a flood**:[26]

- Avoid building in a floodplain unless you elevate and reinforce your home.
- Elevate the furnace, water heater, and electric panel if susceptible to flooding.
- Install check valves in sewer traps to prevent floodwater from backing up into your home.
- Construct barriers (levees, beams, sandbags, and floodwalls) to stop floodwater from entering the building.
- Seal walls in basements with waterproofing compounds to avoid seepage.
- Keep an adequate supply of food, candles, and drinking water in case you are trapped inside your home.

Key Message 2

Climate Change Outpaces Adaptation Planning

Successful adaptation has been hindered by the assumption that climate conditions are and will be similar to those in the past. Incorporating information on current and future climate conditions into design guidelines, standards, policies, and practices would reduce risk and adverse impacts.

The assumption that current and future climate threats and impacts will resemble those of the past is no longer reliably true.[4,27,28] Human-caused carbon pollution in the atmosphere has already pushed many climate-influenced effects—such as the frequency, intensity, or duration of some types of storms and extreme heat, drought, and sea level rise—outside the range of recorded recent natural variability.[4,6,28,29] In addition, improved understanding of climate and Earth system science since the advent of systematic data collection in the 19th century has made it clear that the natural variability of the climate system at regional scales is much larger in places than previously understood. For instance, the southwestern United States was much wetter in the 20th century than in most of the preceding thousand years.

The deviation of climate patterns from the recent historical record is expected to grow even larger in the future because of continuing GHG emissions and because the full impact of previous emissions has not yet been felt due to long delays in the climate system's response to those emissions.[3,4,28] Failure to anticipate and adjust to these changes could be costly.

Adjusting to projected climate risk, rather than relying on interpretations of past impacts, has important implications for the location and design of built human infrastructure, engineering standards, insurance rates, property values, land-use plans and planning frameworks or processes, disaster response preparations, and cropland and forest management. In many respects, such climate risk management has attributes familiar to many decision-makers in businesses and communities that commonly manage or design now for a variety of weather-related risks, including storms, heat waves, water availability threats, and floods. Most organizations also manage other short- and longer-term risks and thus have direct experience with preparing for uncertain future conditions over multiple timescales.

However, climate adaptation is also less familiar to some individuals and organizations in that it requires a complete reversal from the near-universal current assumption of an unchanging climate. Many factors make the reversal of this assumption difficult, including unfamiliarity with climate change datasets and concepts; the need to differentiate among the timescales of weather and climate; the challenge of balancing slow-moving, chronic threats and faster, acute ones; the potential and unknown cascading effects of large-scale global changes on local and regional impacts;[30] and a lack of public awareness that some current and future changes in climate will be slow to accumulate but will take even longer in time to reverse, for the changes that are reversible.[31]

The timescales of climate threats also generally do not align with the scales of governance, impeding adaptation progress and often hindering problem identification and solving. Climate change introduces an unfamiliar new source of uncertainty. Where previously an organization may have created plans using a single, well-understood historical record to project a single set of future climate conditions, it now often faces large numbers

of climate model projections produced with myriad uncertainties whose local implications may differ significantly across each projection.

Key Message 3

Adaptation Entails Iterative Risk Management

Adaptation entails a continuing risk management process; it does not have an end point. With this approach, individuals and organizations of all types assess risks and vulnerabilities from climate and other drivers of change (such as economic, environmental, and societal), take actions to reduce those risks, and learn over time.

To grapple with these challenges, organizations have adopted a wide variety of approaches that, to varying degrees, address the five general stages of adaptation listed above. Iterative risk management provides a comprehensive framework and set of processes appropriate for addressing adaptation challenges.[32,33,34,35,36] The framework includes steps for anticipating, identifying, evaluating, and prioritizing current and future climate risks and vulnerabilities; for choosing an appropriate allocation of effort and resources toward reducing these risks; and for monitoring and adjusting actions over time while continuing to assess evolving risks and vulnerabilities. Risk communication accompanies each of these steps.[33,37,38,39] Iterative risk management helps address equity, economics, and other measures of social well-being and supports participatory stakeholder processes, which can enhance transparency and foster defensible decision-making, an important component of successful adaptation efforts.[40]

Iterative risk management emphasizes that the process of anticipating and responding to climate change does not constitute a single set of judgments at any point in time; rather, it is an ongoing cycle of assessment, action, reassessment, learning, and response.[41] The process helps manage risks that are well known, as well as those that are deeply uncertain due to data limitations or the irreducible unpredictability of some aspects of current and future climate.[33,42]

Iterative risk management is consistent with most of the elements in the many climate adaptation efforts and approaches currently in use,[42,43] including climate vulnerability assessment, iterative risk assessment, and adaptive management as often practiced by federal and other land and resource management agencies,[44] as well as disaster risk management.[45] Using a comprehensive framework helps highlight commonalities and differences across the approaches used by different jurisdictions and sectors, facilitating comparison and learning among their users. It also situates climate adaptation squarely within the broad range of other risk management activities, such as in the financial, engineering, environmental, health, and national security sectors.[2]

Adaptation Actions to Reduce Risk

Steps to implementing iterative risk management help decision-makers compare and allocate investments and identify incentives for managing and reducing risk. The planning and implementation steps of the generalized adaptation framework combine several types of actions[46,47,48,49] that

1. reduce exposure (for example, reduce the presence of people or assets in locations that could be adversely affected by climate impacts);

2. reduce sensitivity (that is, lower the degree to which a system is adversely affected by exposure to climate impacts); and

3. increase adaptive capacity (that is, raise the ability of human and natural systems to prepare for, adjust to, respond to, and recover from experienced or anticipated climate impacts).

For instance, in the time since Superstorm Sandy, New York City has reduced its potential future flood impacts by relocating a limited number of households out of the most flood-prone areas (reduced exposure), raising the height of some structures above the ground so they suffer less damage from any flooding (reduced sensitivity), and training the officials responsible for revising building codes and land-use policies to use the most up-to-date estimates of flood risk (increased adaptive capacity). Enhancing social cohesion—the degree to which those in a community identify with the community and with each other—is also known to increase adaptive capacity, such as the ability to rebound quickly from disasters.[50] More broadly, while adaptive capacity often refers only to the targets of adaptation action (such as communities, ecosystems, and infrastructure), "the ability of institutions themselves to adjust and evolve will be key to their ability to manage for change."[51]

Different populations also have different exposure, sensitivity, and adaptive capacity based on their access to resources and information, their culture, and the quality of governance. Such consideration can usefully inform decisions about the equitable and just allocation of resources in reducing climate risk.[52]

Adapting to Current Variability and Preparing for Future Change

Adaptation addresses two timescales: 1) adapting to current variability, which in any particular location may now be different than suggested by the historical record of climate observations, and 2) preparing for future change. This distinction is useful because some decision-makers may not appreciate the extent to which climate has already changed and because these timescales often call for different types of adaptation actions.

Miami Beach is currently raising the level of its roads and building seawalls to reduce current flooding due to higher sea levels, but it is also choosing the height of these new structures, anticipating that sea levels will be even higher in the future.[53] New York City and the Federal Emergency Management Agency (FEMA) agreed to develop two sets of flood maps, one showing current risk for the purpose of setting insurance rates and the other for the longer-term purposes of setting building codes and land-use planning.[54] The National Park Service, working with the U.S. Army Corps of Engineers, constructed a revetment, or retaining wall, and living shoreline in 2013 to protect the Cockspur Island Lighthouse in Georgia's Fort Pulaski National Monument against erosion and accelerated sea level rise. The new revetment incorporated a wider base than is currently required, enabling the addition of rock to extend its height as sea levels rise in the future.[55] The State of Louisiana's Coastal Protection and Restoration Authority's 2017 Coastal Master Plan has more than 100 structural and coastal restoration projects designed to provide benefits over the next decade and up to 50 years into the future.[56]

These timescale differences relate to the ubiquitous term resilience[57] that is frequently employed in adaptation planning under a spectrum of meanings.[58,59] These range from the ability to withstand and recover from current shocks and stressors while retaining basic functions under conditions of existing and near-term variability to the ability to transform in desirable ways over time as the magnitude of change increases.[60,61,62,63,64,65] Recognizing these timescales in planning, and communicating expectations for change along those timelines,

can also help communities maximize benefits in the near term and identify the most important opportunities for longer-term well-being and resilience.

Organizations are increasingly exploring alternative approaches for replacing the assumption of an unchanging (or stationary) climate in their risk management activities. Vulnerability assessments, a common practice among managers of public lands and natural areas, often evaluate exposure, sensitivity, and adaptive capacity, and provide rankings of the seriousness of various climate risks. Multi-objective approaches, such as structured decision-making,[66] explicitly include multiple measures of well-being in risk assessment and management, often in difficult areas such as protecting cultural resources.[40] Scenarios are used to 1) assess risks over a range of plausible futures that include both changes in socioeconomic trends as well as climate and 2) choose adaptation actions robust over this wide range of futures.[18] California's 2018 Sea-Level Rise Guidance includes probabilistic sea level rise projections and a worst-case scenario, then integrates both with an adaptive pathways approach[67] that encourages robust and flexible plans that can adjust over time if seas rise faster than expected.

Climate risk management requires addressing socioeconomic (for example, future economic, technology, and regulatory conditions) as well as climate uncertainties. Risk management can address such uncertainties, even when they are difficult to characterize with confidence (Ch. 17: Complex Systems, KM 3).[42,68,69,70,71] The water sector is pioneering approaches for incorporating such information in water utility adaptation, including scenarios and other robust decision methods aimed at making successful decisions insensitive to a wide range of uncertainty.[72] Some agencies are beginning to combine both multi-objective and multi-scenario approaches in quantitative tools that identify vulnerabilities and evaluate tradeoffs among adaptive pathways, seeking risk management strategies that perform well across multiple scenarios and measures of well-being.[73,74,75,76] Implementing such methods can require a more complete set of system models than some agencies commonly use in their planning routines, though such tools are becoming increasingly available.[77]

Benefits of Adaptation Can Exceed the Costs

Adaptation can generate significant benefits in excess of its costs. Nationally, estimates of adaptation costs range from tens to hundreds of billions of dollars per year[78,79] but are expected to save several times that over the long run (Ch. 29: Mitigation).[80] The benefits and costs are larger in scenarios with high emissions. Formal benefit analysis is still in its early stages,[81,82] and more research is needed to assess comprehensively the benefits of specific strategies being considered by individuals and organizations.[83] Nonetheless, experience is growing. For instance, the U.S. Department of Housing and Urban Development's National Disaster Resilience Competition required applications to conduct benefit–cost analysis including qualitative and difficult-to-quantify co-benefits, such as economic revitalization and other social benefits.[84]

Key Message 4

Benefits of Proactive Adaptation Exceed Costs

Proactive adaptation initiatives—including changes to policies, business operations, capital investments, and other steps—yield benefits in excess of their costs in the near term, as well as over the long term. Evaluating adaptation strategies involves consideration of equity, justice, cultural heritage, the environment, health, and national security.

To date, there exists considerable guidance on actions in some sectors where benefits exceed costs, though guidance is lacking in many other sectors.[83] Benefit–cost information exists for adaptation responses to storms and rising seas in coastal zones, to riverine and extreme precipitation flooding, and for agriculture at the farm level.[85,86] Some of the actions in these sectors, at least in some locations, appear to have large benefit–cost ratios, both in addressing current variability and in preparing for future change. A benefit–cost ratio greater than 1 suggests a promising project to undertake, because the benefits it generates are greater than its costs. For instance, while sandbags protecting individual houses can, in general, have benefit–cost ratios less than 1, in South Florida sandbags can have a benefit–cost ratio of 20 to 1,[87] and along the Gulf of Mexico coastline, 3 to 1.[88] Along the Gulf of Mexico coastline, levees and seawalls can have benefit–cost ratios ranging from 2.3 to 1.5 to 1 for refineries and petrochemical plants, though the ratios are lower for other assets.[88]

Information on the cost of actions that can achieve common goals is increasing in the water management sector, such as for operational reliability and resilience and environmental protection (Ch. 3: Water) and for responding to extreme heat events (Ch. 14: Human Health). Loss of water services or power during a high heat event, for example, can produce considerable costs that can have cascading effects on other sectors, thereby further driving up costs.[89] The benefits of these adaptive actions against these threats have been studied less because they involve societal and environmental impacts that have been more difficult to quantify, study, and describe systematically.

Some studies quantify large benefits from adaptation actions involving natural systems,[90] such as the decommissioning and restoration of unused forest roads, which decreases erosion and improves fish habitat and water quality; the restoration of beavers to mountain areas, whereby beaver dams improve fish habitat and improve water supply during summer months; and treatment of hazardous fuel to reduce wildland fire risks (Ch. 6: Forests). Some types of storm water management also show large benefits from green infrastructure and other nature-based responses.[91,92] Coastal marsh restoration can sometimes provide benefits of protection against rising sea levels, along with added flood prevention and enhanced biodiversity. One effort involves restoring the river and surrounding lands of the Tidmarsh Wildlife Sanctuary in coastal Massachusetts, a former cranberry farm. The project includes cutting-edge environmental sensors that provide continuous data on marsh restoration, cranberry farm conversion, and climate change impacts and adaptation (see http://www.livingobservatory.org).

Extensive co-benefits may also be available from adaptation, in particular in the ecosystem services and health sectors (Ch. 7: Ecosystems; Ch. 14: Human Health). Coordinated adaptation and GHG mitigation planning may also provide defined co-benefits (Ch. 29: Mitigation, KM 4). For instance, tools are available to help

decision-makers locate wind energy systems away from sensitive ecological sites, without incurring additional costs (for example, see the Nature Conservancy's Biodiversity and Wind Siting Mapping Tool at https://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/newyork/climate-energy/working-with-wind.xml). Designs that provide green space and the use of cool and green roof technologies in cities can reduce heat-island effects, producing multiple benefits and cost reductions by helping to reduce emissions and air pollution, human health risks, and economic losses due to reduced labor productivity.[93,94]

Broader Measures of Well-Being

Benefit–cost analysis provides one important, but not the sole, means to evaluate alternative adaptation actions. Effective adaptation can provide a broad range of benefits that can be difficult to quantify, including improvements in economic opportunity, human health, equity, national security, education, social connectivity, and sense of place, while safeguarding cultural resources and practices and enhancing general environmental quality. Aggregating all these benefits into a single monetary value is not always the best approach,[8,95] since in many cases a lack of data and uncertainty over climate projections and benefit valuations may make it impossible to give a uniform treatment to different types of benefits, thereby implicitly favoring some over others. More fundamentally, different people may value benefits differently.[96] For instance, climate change can have significant impacts on equity and ecosystems, even though individuals can have strongly divergent views on distributional justice and the intrinsic value of nature and thus on how they value such impacts.

Considering various types of outcomes separately in risk management processes—termed multi-objective or multi-criteria analysis in the relevant literature[97]—can facilitate participatory planning processes. This also enhances the fairness of such processes by making more explicit the impacts of climate change on outcomes to different stakeholders, along with the policy tradeoffs among those outcomes. Pittsburgh's EcoInnovation District, in the city's Uptown and Oakland neighborhoods, employs bottom-up planning to improve the environment, support the needs of existing residents, and expand job growth. Louisiana's Comprehensive Master Plan for a Sustainable Coast has five broad objectives: reduce economic losses from flooding, promote sustainable coastal ecosystems, provide coastal habitats that support commerce and recreation, sustain the region's unique cultural heritage, and contribute to the regional and national economy by promoting a viable working coast.[56] The plan contains actions that advance all five objectives, reflecting a set of tradeoffs broadly acceptable to diverse communities in the face of hazards, including coastal subsidence (sinking land) and sea level rise.[98]

Risk management approaches that consider multiple objectives can include a specific focus on equity, with important implications on the content and process of adaptation planning and action.[99] Poor or marginalized populations often face a higher risk from climate change because they live in areas with higher exposure, are more sensitive to climate impacts, or lack adaptive capacity (Ch. 14: Human Health; Ch. 15: Tribes). Prioritizing adaptation actions for such populations may prove more equitable and lead, for instance, to improved infrastructure in their communities and increased focus on efforts to promote social cohesion and community resilience that can improve their capacity to prepare, respond, and recover from disasters. Equity considerations can also lead to the expanded participation of poor or marginalized populations in adaptation planning efforts. This can enhance the fairness of

the process. Moreover, it can positively affect choices regarding the appropriate balance among the resources invested in reducing climate risk and those put toward other social goals, such as employment and education, and inform the most appropriate mix of adaptation actions in each community.[52] Also, at the state and national level, equity considerations for climate adaptation can help allocate an appropriate distribution of resources for adaptation among different local communities.

Key Message 5

New Approaches Can Further Reduce Risk

Integrating climate considerations into existing organizational and sectoral policies and practices provides adaptation benefits. Further reduction of the risks from climate change can be achieved by new approaches that create conditions for altering regulatory and policy environments, cultural and community resources, economic and financial systems, technology applications, and ecosystems.

A significant portion of climate risk can be addressed by mainstreaming; that is, integrating climate adaptation into existing organizational and sectoral investments, policies, and practices. Mainstreaming can make adaptation more likely to succeed because it augments already familiar processes with new information and tools, rather than requiring extensive new structures.[100,101,102] Mainstreaming can also encourage risk management actions that synergistically and coherently address adaptation along with other societal objectives. Mainstreaming can also prompt innovation in existing organizational structures[103,104] by improving their treatment of all types of uncertainty. However, mainstreaming can diminish the visibility of climate adaptation relative to dedicated, stand-alone adaptation approaches[105] and may prove insufficient to address the full range of climate risk, in particular the risks associated with higher GHG concentrations.

Integrating climate adaptation into existing risk management processes requires including climate risks with the other risks an organization regularly assesses and manages; explicitly linking actions that address current climate variability with those needed to address larger, future changes; and linking policies across sectors (for example, energy and water) and jurisdictions. Much adaptation action occurs at the local level, so such linking can be horizontal (that is, among agencies within the same local jurisdiction) and vertical (that is, among different levels of local, state, tribal, and federal governments).[104]

Existing Mainstreaming

Mainstreaming climate adaptation into existing decision processes has begun in many areas, in particular those with well-developed risk management processes such as financial risk reporting, capital investment planning, engineering standards, military planning, and disaster risk management.

A growing number of jurisdictions address climate risk in their land-use, hazard mitigation, capital improvement, and transportation plans. In 2015, FEMA began requiring states to include the projected effects of climate change in their state hazard mitigation plans.[106] A small number of cities explicitly link their coastal plans and their hazard mitigation plans using a common, climate-informed vulnerability analysis to support both types of plans, thereby ensuring that the different city agencies are implementing risk reduction measures—such as land-use measures (reducing exposure), building codes (reducing sensitivity), and warning, evacuation, and recovery measures

(increasing adaptive capacity)—that are synergistic and coordinated.[107] The City of Baltimore used climate-informed estimates of increased current and future storm intensity to design its storm water master plan, which includes green space and bio-swales that capture runoff, to improve water quality and reduce flood risk. California requires its water agencies to address climate change in their water management plans. Through the Department of Energy (DOE) Partnership for Energy Sector Climate Resilience, electric utilities across the country are collaborating with DOE to develop resilience planning guidance, conduct climate change vulnerability assessments, and develop and implement cost-effective resilience solutions (Ch. 4: Energy). The National Oceanic and Atmospheric Administration (NOAA), FEMA, and the U.S. Geological Survey are partnering with states to develop guidelines for integrated climate adaptation, land use, and hazard mitigation planning. Federal agencies have also begun implementing climate-smart management approaches for managing their natural resources (Ch. 7: Ecosystems, KM 2).

Private financial markets are increasingly paying attention to climate risk, for instance, by incorporating such risk accounting into their portfolios. In some cases, financial firms and companies perform climate risk accounting as part of a voluntary or mandatory disclosure system. In a recent report to the G20 (Group of Twenty), the Financial Stability Board's Task Force on Climate-Related Financial Disclosures provided a comprehensive framework for such disclosure and recommended that since "climate-related risks are material risks," they should be disclosed in mainstream (public) financial filings.[108,109] Ratings agencies have also begun to incorporate physical climate risk into credit ratings for corporations, infrastructure bonds, and other public-sector projects. Both Moody's and Standard and Poor's acknowledge emerging risks associated with climate change[110,111] and now embed these risks into their credit ratings.[112] In particularly vulnerable areas, such as South Florida, bond ratings are now beginning to reflect such risks.

The engineering community has begun incorporating climate resilience into its design standards by incorporating information about current and future climate threats and impacts[113] and updating existing engineering standards, codes, regulations, and practices—currently based on stationary climate assumptions.[114] The American Society of Civil Engineers (ASCE) recommends that engineers incorporate climate uncertainty, assess the costs of reducing risks, and follow an adaptive management process. Such a process would begin with low-regret strategies that perform well across a range of futures and periodically update as new information becomes available.[113] The ASCE and the States of California and New York have formed committees to develop such standards.[115]

Other sectors of government and industry are also starting to consider climate risk a major systemic risk. In its 2018 Global Risks Report, the World Economic Forum listed the top five environmental risks—including extreme weather events and temperatures and failures of climate change mitigation and adaptation—in terms of both likelihood and the impact on the global economy.[116] The U.S. military now routinely integrates climate risks into its analysis, plans, and programs,[117] with particular attention paid to climate effects on force readiness, military bases, and training ranges (Ch. 16: International, KM 3).[118,119] Naval Station Norfolk, for example, has replaced existing piers with double-decker piers that are elevated by several more feet and thus more resilient to rising sea levels and extreme weather events (Ch. 1: Overview, Figure 1.8).

Overcoming Up-Front Challenges

While yielding benefits, adaptation also presents challenges. These include difficulties obtaining the necessary funds; insufficient information and relevant expertise; jurisdictional mismatches among those responsible for taking adaptation actions and those who benefit from those actions; conflicting interests among relevant parties; and the pressures on agencies and professionals that serve the public to act cautiously, in particular by seeking to follow long-established procedures and experience.

Insufficient funding often hinders adaptation (Ch. 8: Coastal; Ch. 15: Tribes).[120,121,122] At the local level, adaptation planning and assessment have been supported by a mix of local government funds and federal, state, and foundation grants.[121] Full-scale implementation of the proposals resulting from these adaptation planning and assessment activities would require significantly more resources. In principle, the potential for longer-term savings can be used to generate near-term financing for adaptation efforts. But the mechanisms for doing so are not yet widely in place. Underwriters of municipal bonds, the most common means of financing water infrastructure in the United States, are just beginning to incorporate requirements for long-term sustainability under a changing climate as a condition for going to market.[112]

To the extent that climate resilience becomes an expected and required attribute of decisions concerning infrastructure and other long-term investments, as well as an expected part of asset management and life-cycle cost estimates, financing should become more available for cost-effective adaptation actions.[123] Changing social and economic norms could also affect the availability of financing. Once the implications become widely understood, public expectations, professional standards, and due diligence on the part of financers may similarly discourage investing in long-lived infrastructure designed for stationary conditions, as opposed to currently changing and future climate conditions.[124]

Adaptation often increases up-front costs, thus increasing the salience of steps to reduce those costs. Federal, state, and local governments in the United States spend over $400 billion annually on public infrastructure.[125] Estimates of annual adaptation costs range from tens to hundreds of billions of dollars annually.[78] Taking advantage of new infrastructure investments and capital stock turnover provides one particularly favorable opportunity for low-cost, proactive adaptation in both the public and private sectors.[2] Many jurisdictions and businesses possess significant stocks of deteriorating transportation, water, energy, housing, and other infrastructure, which often already lack resilience to current climate and weather events (Ch. 3: Water; Ch. 4: Energy; Ch. 12: Transportation).[3,126,127] The expected turnover of this capital stock creates opportunities for adaptation but also raises challenges, such as equity concerns, if, for example, upgrading the resilience of housing stock makes it unaffordable for lower-income residents.

Flexible design and adaptive planning can also reduce near-term adaptation costs while keeping options open for future resilience.[128] Such options begin with low-regret options, invest in capacity building, and adjust over time to new information. The Fort Pulaski example cited previously included a new coastal protection structure with an adaptive design that can be inexpensively adjusted as the future risk grows larger. The Metropolitan Water District of Southern California uses adaptive management to organize its 25-year Integrated Resource Plan; factored into its near-term investments in local supplies is the expectation that some investments will be expanded and others reduced as climate, demand, regulatory, and other conditions change in the future.[129] However, explicitly signaling that policies will change in the future may impede

enforcement, make decision-makers seem indecisive, and make it easier for them to succumb to political pressure from special interests.[130]

Catalysts for Adaptation

Catalytic events, external incentives, community interest, leadership, and outside funding all help spur adaptation planning and implementation. Catalytic events, including disasters caused by extreme storms or droughts, often precipitate or accelerate adaptation action,[131,132] as happened with Superstorm Sandy in 2012, Hurricane Katrina in 2005, and the 2011–2016 drought in California (see, for example, Ch. 25: Southwest).

Internal drivers of adaptation include political leadership and policy entrepreneurs.[103] In addition, a recognition of the challenges posed by climate change and an ability to integrate the problem and potential solutions into existing belief and value structures also provide important catalysts for adaptation.

External incentives include the legal requirements, engineering standards, climate-related financial risk disclosure requirements, and changes in insurance coverage. For instance, some existing laws and regulations provide catalysts for adaptation,[133] typically through procedural planning requirements rather than substantive mandates. At the state and local levels, some laws specifically require the consideration of climate change impacts and adaptation options in planning processes, but these cover only a small subset of jurisdictions and geographic areas in the United States.[134,135,136] At the federal level, few laws explicitly promote adaptation, but many can be interpreted as requiring the consideration of climate change impacts on the ability of a federal agency to comply with various statutory and regulatory mandates.[23,137]

Once begun, successful adaptation often entails sustained networks, financing, the sharing of best practices, and champions, as shown in Box 28.3.

Box 28.3: Common Attributes of Effective Adaptation

Factors that shape or contribute to the successful adoption and implementation of adaptation by public-sector organizations include

- plans written by a professional staff and approved by elected officials;
- community engagement, including the participatory development of plans; the formation of action teams or regional collaborations[138] across jurisdictions, sectors, and scales; and public- and private-sector leaders who champion and support the process;
- adaptation actions that address multiple community goals, not just climate change;
- well-structured implementation, including the identification of parties responsible for each step, explicit timelines, explicit and measurable goals, and explicit provisions and timelines for monitoring and updating the plan; and
- adequate funding for the adaptation actions and for sustained community outreach and deliberation.

(Adapted from Brody and Highfield 2005, Berke et al. 2012, Horney et al. 2012, IPCC 2012, NRC 2009, Cutter et. al. 2012, GAO 2016, Wilhite and Pulwarty 2017, Bassett and Shandas 2010, Berke and Lyles 2013, Lyle and Stevens 2014, Hughes 2015, Highfield and Brody 2012, Mimura et al. 2014[47,60,70,139,140,141,142,143,144,145,146,147,148,149].)

Formal and informal networks of government, nongovernmental organizations, and academic, faith-based, and private-sector parties engaged in developing and implementing adaptation are expanding. These networks support individuals, communities, and organizations as they strive to understand and reduce current and future climate risks. Federal, state, and local agencies; nongovernmental organizations; utilities and industry associations; and private-sector consultants have in recent years developed a wide range of written guidance and online platforms intended to support climate adaptation planning and mainstreaming efforts. While not exhaustive, the list includes the 100 Resilient Cities, the C40 Cities Climate Leadership Group, the Urban Sustainability Directors Network (USDN), and the Water Utility Climate Alliance.

Over the past several years, examples of sustained collaborative partnerships between research and management in support of climate risk management have included NOAA's Regional Integrated Sciences and Assessments (RISA), the U.S. Department of Agriculture's (USDA) Climate Hubs, and the Department of the Interior's (DOI) Climate Adaptation Science Centers (CASCs). These regional climate information networks provide data, tools, forecasts, interpretation, and extension services for agencies and communities to build into integrated services and work together to coordinate stakeholder engagement across multiple sectors as new knowledge emerges.[150,151] Some examples include knowledge platforms, such as the Climate Adaptation Knowledge Exchange (www.cakex.org), the Georgetown Climate Center's Adaptation Clearinghouse (http://www.adaptationclearinghouse.org/), and the U.S. Climate Resilience Toolkit website (toolkit.climate.gov); these platforms include directories of practitioners and inventories of data tools for managing natural and built systems in the face of climate change.

More local, targeted resources, such as Louisiana's Coastal Protection Restoration Authority Master Plan Data Viewer (http://cims.coastal.la.gov/masterplan/), offer detailed information about climate risks and probabilities in specific geographic locations to help planners and communities better anticipate and prepare for climate impacts. Such initiatives and networks enable practitioners to share best practices and evaluate and inform adaptation implementation while empowering communities to advance preparedness and resilience efforts across the United States.

Beyond Incremental Change

Integrating climate risk into existing practices can lead to change that is more than incremental. For instance, it often proves profitable in the near term to build in low-lying areas subject to future extreme flooding[152] rather than in areas with lower future risk. Updated flood maps and risk-adjusted insurance rates would likely lead to different patterns of development.[153] In many cases, however, addressing the full range of future climate change requires substantial changes in organizational practices and procedures, in public- and private-sector institutions, in individual and societal expectations and norms, in capital investment planning, and in laws.[154,155] Decision-makers may wish to take active steps to anticipate and steer change in desired directions and to avoid the unanticipated consequences of ad hoc or crisis-based responses. In some cases, this involves seeking, legitimizing, and accelerating large changes, rather than attempting to retain today's conditions as long as possible.[10,156,157]

Reducing climate risk often requires managing interdependent systems in ways that transcend current jurisdictional and sectoral boundaries (Ch. 4: Energy; Ch. 17: Complex Systems, KM 3). Water, electric power supply, and agriculture often depend critically on one another (see Ch. 17: Complex Systems, KM 1) but are not treated

similarly for potential adaptation actions. Effective climate risk management often requires closer coordination among regulatory agencies and, in some cases, may necessitate some restructuring. For instance, the City of Los Angeles's One Water LA program requires multiple city agencies to coordinate on integrated management of the city's water, land-use, and flood control actions.[158] Major reforms can prove difficult and often occur only in response to major system shocks, such as reforms to the Stafford Act after Hurricane Katrina[159,160,161] or the consolidation of many local water agencies in Australia into a small number of large, regional organizations during a decade of severe drought.[162]

Some sectors are already taking actions that go beyond integrating climate risk into current practices. Faced with substantial climate-induced future changes, including new invasive species and shifting ranges, ecosystem managers have already begun to adopt novel approaches, such as assisted migration and wildlife corridors (Ch. 7: Ecosystems, KM 2), and to rethink the goals of conservation management.[163] Many millions of Americans live in coastal areas threatened by sea level rise; in all but the very lowest sea level rise projections, retreat will become an unavoidable option in some areas of the U.S. coastline (Ch. 8: Coastal, KM 1). The Federal Government has already provided resources for the relocation of some communities, such as the Biloxi-Chitimacha-Choctaw tribe from Isle de Jean Charles in Louisiana. But the potential need for millions of people and billions of dollars of coastal infrastructure to be relocated in the future creates challenging legal, financial, and equity issues that have not yet been addressed.

The ability of adaptation to reduce severe climate impacts like these will ultimately depend less on scientific uncertainties and the ability to implement engineering solutions than on perceived loss of culture and identity, in particular identities associated with unique cultural heritage sites and a sense of place (Ch. 8: Coastal; Ch. 15: Tribes, KM 2).[68] Because different regions and groups face different levels of risk and have differing abilities to respond, considerations of equity and justice influence judgments about any limits to adaptation.[52,68]

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Traceable Accounts

Process Description

The scope for this chapter was determined by the Fourth National Climate Assessment (NCA4) Federal Steering Committee, which is made up of representatives from the U.S. Global Change Research Program member agencies. The scope was also informed by research needs identified in the Third National Climate Assessment (NCA3). Authors for this NCA4 chapter were selected to represent a range of public- and private-sector perspectives and experiences relevant to adaptation planning and implementation.

This chapter was developed through technical discussions of relevant evidence and expert deliberation by chapter authors during teleconferences, e-mail exchanges, and a day-long in-person meeting. These discussions were informed by a comprehensive literature review of the evidence base for the current state of adaptation in the United States. The author team obtained input from outside experts in several important areas to supplement its expertise.

Key Message 1

Adaptation Implementation Is Increasing

Adaptation planning and implementation activities are occurring across the United States in the public, private, and nonprofit sectors. Since the Third National Climate Assessment, implementation has increased but is not yet commonplace. (*High Confidence*)

Description of evidence base

There exists extensive documentation in the gray literature of specific adaptation planning and implementation activities underway by local, state, regional, and federal agencies and jurisdictions. The literature also contains reports that attempt to provide an overview of these activities, such as the recent set of case studies in Vogel et. al. (2017).[14] Websites, such as those of the Georgetown Climate Center (http://www.georgetownclimate.org), provide summaries and examples of adaptation activities in the United States. The sectoral and regional chapters in this National Climate Assessment also provide numerous examples of adaptation planning and implementation activities. The literature also offers work that aims to provide surveys of large numbers of adaptation activity, such as Moser et. al. (2018)[121] and Stults and Woodruff (2016).[164]

Major uncertainties

While the amount of adaptation-related activity is clearly increasing, the lack of clear standards and the diverse lexicon used in different sectors make it difficult to systematically compare different adaptation activities at the level of outcomes across sectors and regions of the country. In addition, publicly available adaptation plans may never actually result in implementation. It is thus difficult to provide a quantitative assessment of the increase in adaptation activity other than just counting plans and initiatives. Given the reliance on small-sample surveys, judgments about the distribution of adaptation actions across categories have potentially large errors that are difficult to estimate. In addition, it is difficult to assess the contribution of these activities to concrete outcomes such as risk reduction or current and future improvements to well-being, security, and environmental protection.[130] There also exists little gap analysis that compares any given set of

adaptation activities with what might be appropriate according to some normative standard or what might be reasonably achieved. Thus, while adaptation activities are clearly increasing in the United States, scant evidence exists for judging their consequences.

Description of confidence and likelihood

There is *high confidence* that the amount of adaptation activity, in particular implementation activity, is increasing. There is less agreement and evidence regarding the consequences of this activity.

Key Message 2

Climate Change Outpaces Adaptation Planning

Successful adaptation has been hindered by the assumption that climate conditions are and will be similar to those in the past. Incorporating information on current and future climate conditions into design guidelines, standards, policies, and practices would reduce risk and adverse impacts. (*High Confidence*)

Description of evidence base

The assumption that the historical record of events and variability will be the same in the future is called the stationarity assumption[27] and has guided planning for climate and weather events in most places for most of recorded history. The evidence is strong that the stationarity assumption is no longer valid for all impacts and variability in all locations, because climate change is altering both the events and their variability.[3,4,28,165] Regional chapters in this assessment establish the climate variables for which, and the extent to which, non-stationarity has been confirmed around the United States. These chapters also provide extensive documentation of cases in which failure to adapt to current and future climate conditions can cause significant adverse impacts.

Major uncertainties

While significant uncertainties can exist in estimating the extent to which current variability differs from historic observations in any particular location, there is robust evidence that such differences do occur in many locations (see Ch. 18: Northeast; Ch. 19: Southeast; Ch. 20: U.S. Caribbean; Ch. 21: Midwest; Ch. 22: N. Great Plains; Ch. 23: S. Great Plains; Ch. 24: Northwest; Ch. 25: Southwest; Ch. 26: Alaska; and Ch. 27: Hawai‘i & Pacific Islands).[5,6,28,166] However, the development and use of analytic tools, decision-making processes, and application mechanisms built on the assumption of non-stationarity lag significantly behind the growing realization that stationarity is no longer a sound basis for long-range planning.[167] Nonetheless, new techniques are being applied.[10,72,168] For example, scenario planning can provide alternative actions that can be carried out if different impacts occur.[70,71]

Description of confidence and likelihood

There is *high confidence* that most organizations' planning is currently based on extensions from the record of local climate conditions.[169]

Key Message 3

Adaptation Entails Iterative Risk Management

Adaptation entails a continuing risk management process; it does not have an end point. With this approach, individuals and organizations of all types assess risks and vulnerabilities from climate and other drivers of change (such as economic, environmental, and societal), take actions to reduce those risks, and learn over time. (*High Confidence*)

Description of evidence base

Evidence from a large body of literature and observations of experience support the judgment that iterative risk management is a useful framework (e.g., National Research Council 2009, America's Climate Choices 2010, Kunreuther et al. 2012[142,170,171]). The literature also suggests its conceptual similarity with other methods that use different names.

Major uncertainties

The literature and practice of climate change are undergoing a process of maturation and convergence. The process began with many organizations and sectors developing their own approaches and terminology in response to climate risks, meaning that a wide variety of approaches still exist in the field. We believe that the field will progress and converge on the most effective approaches, including iterative risk management. But this convergence is still in process, and the outcome remains uncertain.

Description of confidence and likelihood

Significant agreement and strong evidence provide *high confidence* that adaptation is a form of iterative risk management and that this is an appropriate framework for understanding, addressing, and communicating climate-related risks.[33]

Key Message 4

Benefits of Proactive Adaptation Exceed Costs

Proactive adaptation initiatives—including changes to policies, business operations, capital investments, and other steps—yield benefits in excess of their costs in the near term, as well as over the long term (*medium confidence*). Evaluating adaptation strategies involves consideration of equity, justice, cultural heritage, the environment, health, and national security (*high confidence*).

Description of evidence base

Both limited field applications and literature reviews highlight adaptation co-benefits, including those associated with equity considerations.[83] Near-term benefits are assessed from observations of adaptation results, as well as from comparisons to similar situations without such responses; longer-term benefits are generally assessed from projections.

Major uncertainties

Benefits are based on understanding the relevant systems so that one can compare similar cases and construct counterfactuals. Such understanding is excellent for many engineered systems (for example, how a storm drain performs under various rainfall scenarios) but is less robust for many biological systems. Benefit–cost ratios can have large uncertainties associated with estimates of costs, the projection of benefits, and the economic valuation of benefits. In addition, because expected differences in benefit–cost ratios are sufficiently large and the number of current examples is sufficiently low, there are large uncertainties in applying results from one case to another.

Description of confidence and likelihood

There is suggestive evidence that provides *medium confidence* that many proactive adaptation actions offer significant benefits that exceed their costs. However, because of a small sample size and insufficient evaluation, it is in general hard to know the extent to which this is true in any particular case. There is strong agreement that evaluating adaptation involves consideration of a wide range of measures of social well-being.

Key Message 5

New Approaches Can Further Reduce Risk

Integrating climate considerations into existing organizational and sectoral policies and practices provides adaptation benefits. Further reduction of the risks from climate change can be achieved by new approaches that create conditions for altering regulatory and policy environments, cultural and community resources, economic and financial systems, technology applications, and ecosystems. (*High Confidence*)

Description of evidence base

There is significant agreement, but only case study evidence, that effective adaptation can be realized by mainstreaming.[100,101,102] Significant evidence exists regarding the scale of longer-term adaptation required in some climate futures based on modeling studies. Significant agreement, but less direct evidence, exists on the scale of organizational and other changes needed to implement these adaptation actions.

Major uncertainties

It is not well understood how community acceptance of needed adaptations develops. This presents both a barrier to the implementation of adaptation measures and an opportunity for additional research into ways to close this gap in understanding. Additionally, a need exists to clarify the co-benefits of addressing multiple threats and opportunities. Effective adaptation also depends on networks of collaboration among researchers and practitioners and the long-term support of monitoring networks. The sustainability of both types of networks is a major uncertainty. Their effectiveness is both an uncertainty and major research need.

Description of confidence and likelihood

There is significant agreement that provides *high confidence*, in at least some cases, that both 1) mainstreaming climate information into existing risk management and 2) creating enabling environments and institutions to improve adaptation capacity, implementation, and evaluation reduce risk, produce co-benefits across communities and sectors, and help secure economic investments into the future.

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29 Reducing Risks Through Emissions Mitigation

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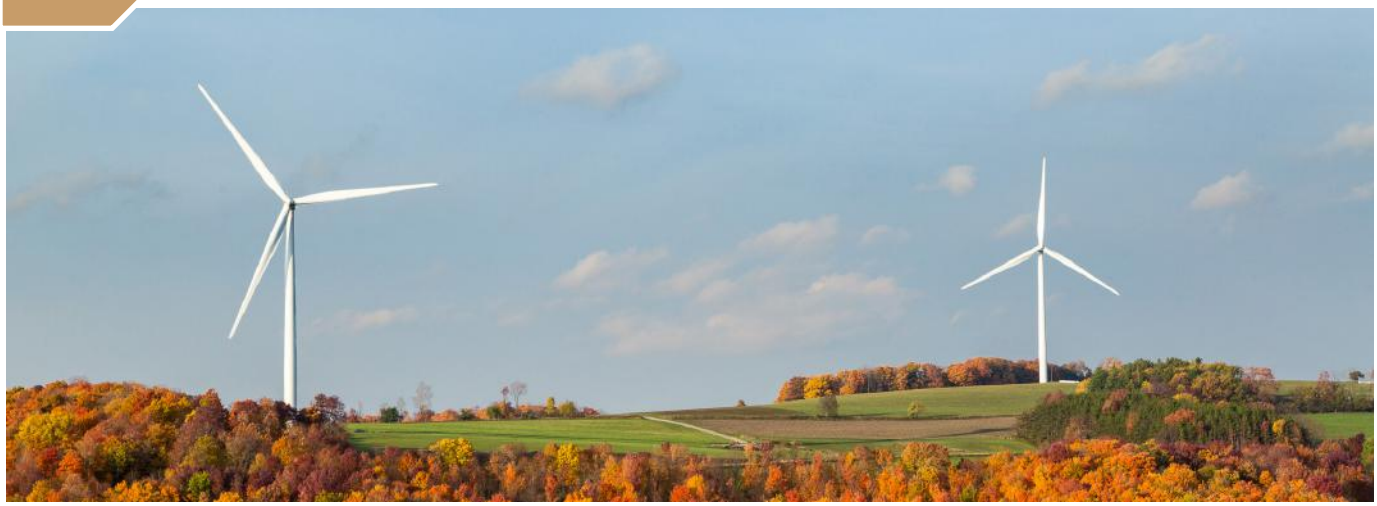

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Key Message 1

Mitigation-Related Activities Within the United States

Mitigation-related activities are taking place across the United States at the federal, state, and local levels as well as in the private sector. Since the Third National Climate Assessment, a growing number of states, cities, and businesses have pursued or deepened initiatives aimed at reducing emissions.

Key Message 2

The Risks of Inaction

In the absence of more significant global mitigation efforts, climate change is projected to impose substantial damages on the U.S. economy, human health, and the environment. Under scenarios with high emissions and limited or no adaptation, annual losses in some sectors are estimated to grow to hundreds of billions of dollars by the end of the century. It is very likely that some physical and ecological impacts will be irreversible for thousands of years, while others will be permanent.

Key Message 3

Avoided or Reduced Impacts Due to Mitigation

Many climate change impacts and associated economic damages in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions, though the magnitude and timing of avoided risks vary by sector and region. The effect of near-term emissions mitigation on reducing risks is expected to become apparent by mid-century and grow substantially thereafter.

Key Message 4

Interactions Between Mitigation and Adaptation

Interactions between mitigation and adaptation are complex and can lead to benefits, but they also have the potential for adverse consequences. Adaptation can complement mitigation to substantially reduce exposure and vulnerability to climate change in some sectors. This complementarity is especially important given that a certain degree of climate change due to past and present emissions is unavoidable.

Executive Summary

Current and future emissions of greenhouse gases, and thus emission mitigation actions, are crucial for determining future risks and impacts of climate change to society. The scale of risks that can be avoided through mitigation actions is influenced by the magnitude of emissions reductions, the timing of those reductions, and the relative mix of mitigation strategies for emissions of long-lived greenhouse gases (namely, carbon dioxide), short-lived greenhouse gases (such as methane), and land-based biologic carbon.[1] Many actions at national, regional, and local scales are underway to reduce greenhouse gas emissions, including efforts in the private sector.

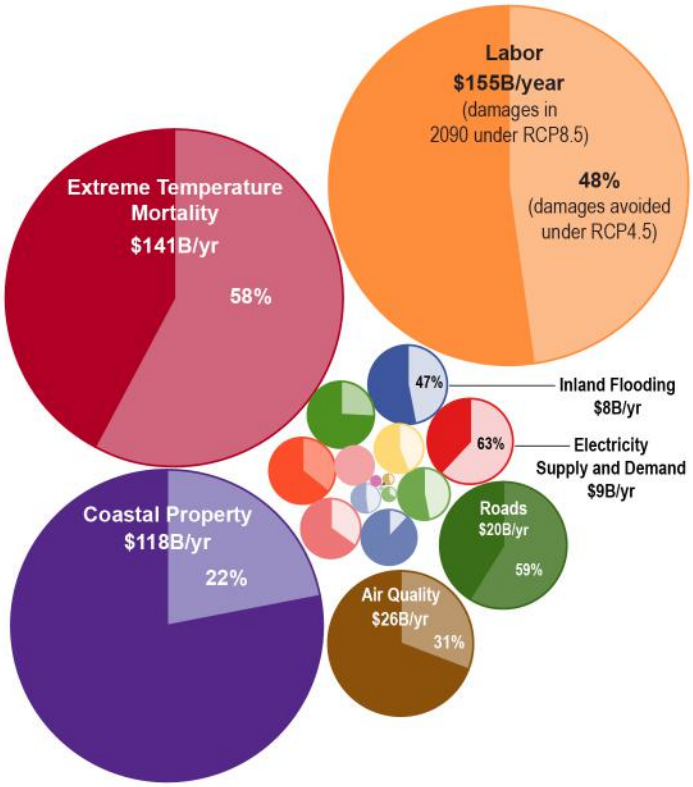
Climate change is projected to significantly damage human health, the economy, and the environment in the United States, particularly under a future with high greenhouse gas emissions. A collection of frontier research initiatives is underway to improve understanding and quantification of climate impacts. These studies have been designed across a variety of sectoral and spatial scales and feature the use of internally consistent climate and socioeconomic scenarios. Recent findings from these multisector modeling frameworks demonstrate substantial and far-reaching changes over the course of the 21st century—and particularly at the end of the century—with negative consequences for a large majority of sectors, including infrastructure and human health.[2,3,4,5] For sectors where positive effects are observed in some regions or for specific time periods, the effects are typically dwarfed by changes happening overall within the sector or at broader scales.

Recent studies also show that many climate change impacts in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions. While the difference in climate outcomes between scenarios is more modest through the first half of the century,[6] the effect of mitigation in avoiding climate change impacts typically becomes clear by 2050 and increases substantially in magnitude thereafter. Research supports that early and substantial mitigation offers a greater chance of avoiding increasingly adverse impacts.

The reduction of climate change risk due to mitigation also depends on assumptions about how adaptation changes the exposure and vulnerability of the population. Physical damages to coastal property and transportation infrastructure are particularly sensitive to adaptation assumptions, with proactive measures estimated to be capable of reducing damages by large fractions. Because society is already committed to a certain amount of future climate change due to past and present emissions and because mitigation activities cannot avoid all climate-related risks, mitigation and

adaptation activities can be considered complementary strategies. However, adaptation can require large up-front costs and long-term commitments for maintenance, and uncertainty exists in some sectors regarding the applicability and effectiveness of adaptation in reducing risk. Interactions between adaptation and mitigation strategies can result in benefits or adverse consequences. While uncertainties still remain, advancements in the modeling of climate and economic impacts, including current understanding of adaptation pathways, are increasingly providing new capabilities to understand and quantify future effects.

Projected Damages and Potential for Risk Reduction by Sector



Annual Economic Damages in 2090		
Sector	**Annual damages under RCP8.5**	**Damages avoided under RCP4.5**
Labor	$155B	48%
Extreme Temperature Mortality◊	$141B	58%
Coastal Property◊	$118B	22%
Air Quality	$26B	31%
Roads◊	$20B	59%
Electricity Supply and Demand	$9B	63%
Inland Flooding	$8B	47%
Urban Drainage	$6B	26%
Rail◊	$6B	36%
Water Quality	$5B	35%
Coral Reefs	$4B	12%
West Nile Virus	$3B	47%
Freshwater Fish	$3B	44%
Winter Recreation	$2B	107%
Bridges	$1B	48%
Munic. and Industrial Water Supply	$316M	33%
Harmful Algal Blooms	$199M	45%
Alaska Infrastructure◊	$174M	53%
Shellfish*	$23M	57%
Agriculture*	$12M	11%
Aeroallergens*	$1M	57%
Wildfire	−$106M	−134%

The total area of each circle represents the projected annual economic damages (in 2015 dollars) under a higher scenario (RCP8.5) in 2090 relative to a no-change scenario. The decrease in damages under a lower scenario (RCP4.5) compared to RCP8.5 is shown in the lighter-shaded area of each circle. Where applicable, sectoral results assume population change over time, which in the case of winter recreation leads to positive effects under RCP4.5, as increased visitors outweigh climate losses. Importantly, many sectoral damages from climate change are not included here, and many of the reported results represent only partial valuations of the total physical damages. See EPA 2017 for ranges surrounding the central estimates presented in the figure; results assume limited or no adaptation.[2] Adaptation was shown to reduce overall damages in sectors identified with the diamond symbol but was not directly modeled in, or relevant to, all sectors. Asterisks denote sectors with annual damages that may not be visible at the given scale. Only one impact (wildfire) shows very small positive effects, owing to projected landscape-scale shifts to vegetation with longer fire return intervals (see Ch. 6: Forests for a discussion on the weight of evidence regarding projections of future wildfire activity). The online version of this figure includes value ranges for numbers in the table. Due to space constraints, the ranges are not included here. *From Figure 29.2 (Source: adapted from EPA 2017).*[2]

Introduction

This chapter assesses recent advances in climate science and impacts, adaptation, and vulnerability research that have improved understanding of how potential mitigation pathways can avoid or reduce the long-term risks of climate change within the United States. This chapter does not evaluate technology options, costs, or the adequacy of existing or planned mitigation efforts relative to meeting specific policy targets, as those topics have been the subject of domestic (e.g., Executive Office of the President 2016, CCSP 2007, DeAngelo et al. 2017, NRC 2015[7,8,9,10]) and international analyses (e.g., Fawcett et al. 2015, Clarke et al. 2014[11,12]). Also, this chapter does not assess the potential roles for carbon sinks (or storage) in mitigation, which are discussed in Chapter 5: Land Changes, and in the Second State of the Carbon Cycle Report.[13] Further, it is beyond the scope of this chapter and this assessment to evaluate or recommend policy options.

USGCRP defines risk as threats to life, health and safety, the environment, economic well-being, and other things of value. Risks are often evaluated in terms of how likely they are to occur (probability) and the damages that would result if they did happen (consequences).

Both mitigation and adaptation responses to climate change are likely to occur as part of an iterative risk management strategy in which initial actions are modified over time as learning occurs (Ch. 28: Adaptation). This chapter focuses primarily on the early stages of this iterative process in which risks and vulnerabilities are identified and the potential climate impacts of emissions scenarios are assessed.

Box 29.1: Options for Reducing or Removing Greenhouse Gases

Mitigation refers to measures to reduce the amount and speed of future climate change by reducing emissions of greenhouse gases (GHGs) or by increasing their removal from the atmosphere. Emission reduction measures include replacing conventional, CO_2-emitting fossil fuel energy technologies or systems with low- or zero-emissions ones (such as wind, solar, nuclear, biofuels, fossil energy with carbon capture and storage, and energy efficiency measures), as well as changing technologies and practices in order to lower emissions of other GHGs such as methane, nitrous oxide, and hydrofluorocarbons.[7,14,15] Measures that enhance the removal of CO_2 from the atmosphere (see Box 29.3) include changing land-use and management practices to store carbon in plants, trees, and soils; increasing ocean carbon storage through biological or chemical means; capturing atmospheric CO_2 through engineered chemical reactions and storing it in geologic reservoirs; or converting terrestrial biomass into energy while capturing and storing the CO_2.[16] Using captured CO_2 in products such as polymers and cement is a potential alternative to geologic storage.[17]

The adoption of these measures may be promoted through a variety of policy instruments, such as emissions pricing (that is, GHG emission fees or emissions caps with permit trading), regulations and standards (such as emission standards, technology requirements, and building codes), subsidies (for example, tax incentives and rebates), and public funding for research, development, and demonstration programs.

Timing and Magnitude of Action

Current and future emissions, and thus emissions mitigation actions, are crucial for determining future risks and impacts. The scale of risks that can be avoided through mitigation actions is influenced by the magnitude of emissions reductions, the timing of those emissions reductions, and the relative mix of mitigation strategies for emissions of long-lived GHGs (namely, CO_2), short-lived GHGs (such as methane), and land-based biologic carbon.[1] Intentional removal of CO_2 from the atmosphere, often referred to as negative emissions, or other climate interventions have also been proposed[10,18] and may play a role in future mitigation strategies (see Box 29.3).

Net cumulative CO_2 emissions in the industrial era will largely determine long-term global average temperature change[9] and thus the risks and impacts associated with that change in the climate. Large reductions in present-day emissions of the long-lived GHGs are estimated to have modest temperature effects in the near term (over the next couple decades), but these emission reductions are necessary to achieve any long-term objective of preventing warming of any desired magnitude.[9] Decisions that decrease or increase emissions over the next few decades will set into motion the degree of impacts that will likely last throughout the rest of this century, with some impacts (such as sea level rise) lasting for thousands of years or even longer.[19,20,21]

Meeting any climate stabilization goal, such as the oft-cited objective of limiting the long-term globally averaged temperature to 2°C (3.6°F) above preindustrial levels, necessitates that there be a physical upper limit on the cumulative amount of CO_2 that can be added to the atmosphere.[9] Early and substantial mitigation offers a greater chance for achieving a long-term goal, whereas delayed and potentially much steeper emissions reductions jeopardize achieving any long-term goal given uncertainties in the physical response of the climate system to changing atmospheric CO_2, mitigation deployment uncertainties, and the potential for abrupt consequences.[11,22,23] Early efforts also enable an iterative approach to risk management, allowing stakeholders to respond to what is learned over time about climate impacts and the effectiveness of available actions (Ch. 28: Adaptation).[24,25,26] Evidence exists that early mitigation can reduce climate impacts in the nearer term (such as reducing the loss of perennial sea ice and effects on ice-dwelling species) and, in the longer term, prevent critical thresholds from being crossed (such as marine ice sheet instability and the resulting consequences for global sea level change).[27,28,29,30]

State of Emissions Mitigation Efforts

Actions are currently underway at global, national, and subnational scales to reduce GHG emissions. This section provides an overview of agreements, policies, and actions being taken at various levels.

Long-Term Temperature Goals and the Paris Agreement

The idea of limiting globally averaged warming to a specific value has long been examined in the scientific literature and, in turn, gained attention in policy discourse (see DeAngelo et al. 2017 for additional information[9]). Most recently, the Paris Agreement of 2015 took on the long-term aims of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels".[31] These targets were developed with the goal of avoiding the most severe climate impacts; however, they should not be viewed as thresholds below which there are zero risks and above which

numerous tipping points occur (that is, a point at which a change in the climate triggers a significant environmental event, which may be permanent). In order to reach the Paris Agreement's long-term temperature goal, Parties to the Agreement "aim to reach global peaking of GHG emissions as soon as possible . . . and to undertake rapid reductions thereafter." Many countries announced voluntary, nonbinding GHG emissions reduction targets and related actions in the lead-up to the Paris meeting; these announcements addressed emissions through 2025 or 2030 and took a range of forms.[31] The Paris Agreement has been ratified by 180 Parties to the UN Framework Convention on Climate Change, which account for 88% of global GHG emissions.[32,33]

Achieving the Paris Agreement target of limiting global mean temperature to less than 2°C (3.6°F) above preindustrial levels requires substantial reductions in net global CO_2 emissions prior to 2040 relative to present-day values and likely requires net CO_2 emissions to become zero or possibly negative later in the century, relying on as-yet unproven technologies to remove CO_2 from the atmosphere. To remain under this temperature threshold with two-thirds likelihood, future cumulative net CO_2 emissions would need to be limited to approximately 230 gigatons of carbon (GtC), an amount that would be reached in roughly the next two decades assuming global emissions follow the range between the RCP4.5 and RCP8.5 scenarios.[9] Achieving global GHG emissions reduction targets and actions announced by governments in the lead-up to the 2015 Paris climate conference would hold open the possibility of meeting the 2°C (3.6°F) temperature goal, whereas there would be virtually no chance if net global emissions followed a pathway well above those implied by country announcements.[9]

In June 2017, the United States announced its intent to withdraw from the Paris Agreement.[34] The statement is available online: https://www.whitehouse.gov/briefings-statements/statement-president-trump-paris-climate-accord/. The earliest effective date of formal withdrawal is November 4, 2020. Some state governments, local governments, and private-sector entities have announced pledges to reduce emissions in the context of long-term temperature aims consistent with those outlined in the Paris Agreement.[35,36]

Key Message 1

Mitigation-Related Activities Within the United States

Mitigation-related activities are taking place across the United States at the federal, state, and local levels as well as in the private sector. Since the Third National Climate Assessment, a growing number of states, cities, and businesses have pursued or deepened initiatives aimed at reducing emissions.

Many activities within the public and private sectors either aim to or have the effect of reducing these emissions. Fossil fuel combustion accounts for 77% of the total U.S. GHG emissions (using the 100-year global warming potential), with agriculture, industrial processes, and methane from fossil fuel extraction and processing as well as waste accounting for the remainder.[37] A 100-year global warming potential is an index measuring the radiative forcing following an emission of a unit mass of a given substance, accumulated over one hundred years, relative to that of the reference substance, CO_2.[38] At the federal level, a number of measures have been implemented to promote advanced, low-carbon energy technologies and fuels, including energy efficiency. Broadly considered, these measures include

GHG regulations; other rules and regulations with climate co-benefits; codes and standards; research, development, and demonstration projects and programs; federal procurement practices; voluntary programs; and various subsidies (such as production and investment tax credits).[14,39] Federal measures to address sources other than fossil fuel combustion include agriculture and forestry programs to increase soil and forest carbon sequestration and minimize losses through wildfire or other land-use processes, regulations to phase down hydrofluorocarbons, and standards for reducing methane emissions from fossil fuel extraction and processing.[14] The Administration is currently reviewing many of these measures through the lens of Executive Order 13783, which aims to ease regulatory burdens on "the development or use of domestically produced energy resources, with particular attention to oil, natural gas, coal, and nuclear energy resources."[40]

State, local, and tribal government mitigation approaches include comprehensive emissions reduction strategies as well as sector- and technology-specific policies designed for many reasons. As shown in Figure 29.1a, at least 455 cities support emissions reductions in the context of global efforts, including 110 with emissions reduction targets.[36] At the state level, the color shown on each state indicates the total number of activities taken in that state across six policy areas: GHG target/cap/pricing; renewable/carbon dioxide capture and storage (CCS)/nuclear; transportation; energy efficiency; non-CO_2 GHG; and forestry and land use.[36] Figure 29.1b shows the number of activities by policy area for each state. For example, states in the Northeast take part in the Regional Greenhouse Gas Initiative, a mandatory market-based effort to reduce power sector emissions.[41] California has a legal mandate to reduce emissions 40% below 1990 levels by 2030, and in a 2017 law, the state extended its emissions trading program to 2030, as well. Several states have adopted voluntary pledges to reduce emissions. Technology-specific approaches include targets to increase the use of renewable energy such as wind and solar, zero- or low-emissions transportation options, and energy efficient technologies and practices.[42,43] Many tribes are also prioritizing energy-efficiency and renewable-energy projects (Ch. 15: Tribes, KM 1).[44] Mitigation activities related to methane and forestry/land-use activities are growing in number and vary by locale.

In the private sector, many companies seek to provide environmental benefits for a variety of reasons, including supporting environmental stewardship, responding to investor demands for prudent risk management, finding economic opportunities in efforts to reduce GHG emissions, and, in the case of multinationals, meeting mitigation mandates in the European Union or other jurisdictions. Since the last National Climate Assessment, private companies have increasingly taken inventory of their emissions and moved forward to implement science-based emissions reduction targets as well as internal carbon prices.[36] The Carbon Disclosure Project[46] is one example of a voluntary program where companies register their pledges to reduce GHG emissions and/or to manage their climate risks. Corporate purchases of and commitments to purchase renewable energy have increased over the last decade.[47]

Mitigation-Related Activities at State and Local Levels

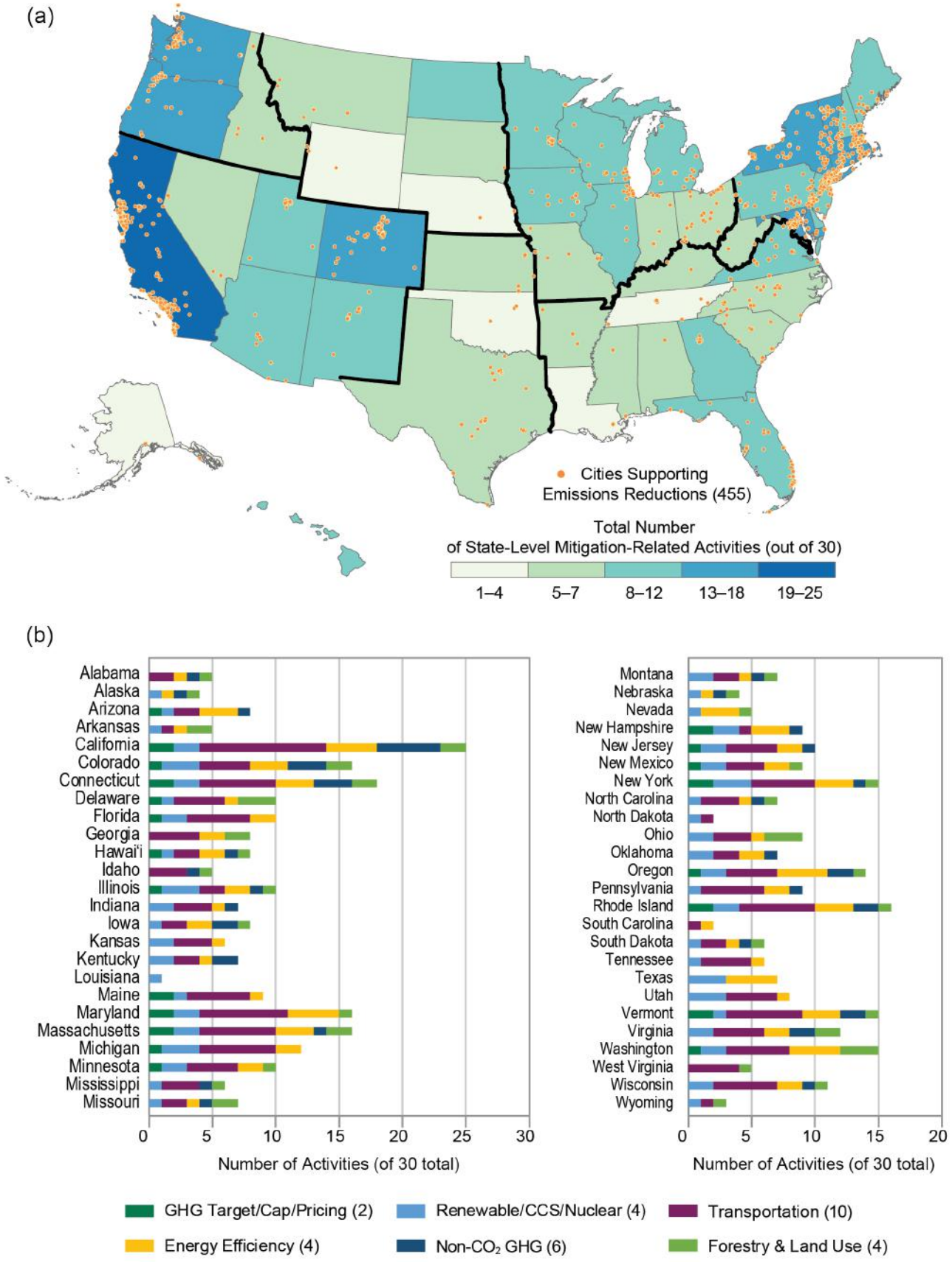


Figure 29.1: The map (a) shows the number of mitigation-related activities at the state level (out of 30 illustrative activities) as well as cities supporting emissions reductions; the chart (b) depicts the type and number of activities by state.[36] Several territories also have a variety of mitigation-related activities including American Sāmoa, the Federated States of Micronesia, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands.[42,45] Sources: (a) EPA and ERT, Inc.; (b) adapted from America's Pledge 2017.[36]

Market forces and technological change, particularly within the electric power sector, have contributed to a decline in U.S. GHG emissions over the past decade. In 2016, U.S. emissions were at their lowest levels since 1994.[37] Power sector emissions were 25% below 2005 levels in 2016, the largest sectoral reduction over this time.[37] This decline was in large part due to increases in natural gas generation as well as renewable energy generation and energy efficiency (Ch. 4: Energy, KM 2).[48] Given these changes in the power sector, the transportation sector currently has the largest annual sectoral emissions (Ch. 12: Transportation). As of the writing of this report, projections of U.S. fossil fuel CO_2 and other GHG emissions show flat or declining trajectories over the next decade, with a central estimate of about 15%–20% below 2005 levels by 2025.[49,50] Prior to the adoption of the Paris Agreement, the United States put forward a nonbinding "intended nationally determined contribution" of reducing emissions 26%–28% below 2005 levels in 2025. On June 1, 2017, President Trump announced that the United States would cease implementation of this nationally determined contribution. Some state and local governments, as well as private-sector entities, have announced emission reduction pledges which aim to be consistent with the nonbinding target.[35,36] For more information on trends in, drivers of, and potential efforts to address U.S. GHG emissions, see the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.[37]

Reducing Impacts Through Mitigation

To understand how large-scale emissions mitigation can reduce climate impacts, it is useful to look at how the impacts change under various emissions scenarios. In recent years, the science and economics of estimating future climate change impacts have advanced substantially, with increasing emphasis on interdisciplinary approaches to investigate impacts, vulnerabilities, and responses.[51,52,53] These advances have enabled several ongoing frontier research initiatives to improve understanding and quantification of climate impacts at various spatial scales ranging from global to local levels. This section describes findings for the United States from a selection of recent multisector coordinated modeling frameworks listed in Table 29.1, which are frequently cited throughout this chapter because each report provides modeling results across multiple sectors and scenarios similar to those developed for this report. These approaches commonly feature the use of internally consistent climate and socioeconomic scenarios and underlying assumptions across a variety of sectoral analyses. While research projecting physical and economic impacts in the United States has increased considerably since the Third National Climate Assessment (NCA3), it is important to note that this literature is incomplete in its coverage of the breadth of potential impacts.

Collaboration or Project Name	Host/Lead Organization and References	Sectors Covered	Coverage
Benefits of Reduced Anthropogenic Climate changE (BRACE)	National Center for Atmospheric Research (O'Neill et al. 2017)[4]	Heat extremes and health, agriculture and land use, tropical cyclones, sea level rise, drought and conflict	Global
Costs of Inaction and Resource scarcity: Consequences for Long-term Economic growth (CIRCLE)	Organisation for Economic Co-operation and Development (OECD 2015)[55]	Tourism, agriculture, coastal, energy, extreme precipitation events, health	Global
Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)	Potsdam Institute for Climate Impact Research (Huber et al. 2014)[56]	Water, agriculture, biomes, infrastructure, health/malaria, fishery, permafrost	Global
American Climate Prospectus (ACP)	Climate Impact Lab (Houser et al. 2015; Hsiang et al. 2017)[3,5]	Agriculture, health, labor productivity, crime and conflict, coastal, energy	United States
Climate Change Impacts and Risk Analysis (CIRA)	U.S. Environmental Protection Agency (EPA 2015, 2017)[2,57]	More than 20 specific impacts categorized into 6 broad sectors: health (including labor productivity), infrastructure, electricity, water resources, agriculture, ecosystems	United States
California Climate Change Assessments	State of California (Cayan et al. 2008, 2013; California Energy Commission 2006)[58,59,60]	Public health, agriculture, energy, coastal, water resources, ecosystems, wildfire, recreation	State-Level
Colorado Climate Change Vulnerability Study	Colorado Energy Office (Gordon and Ojima 2015)[61]	Ecosystems, water, agriculture, energy, transportation, recreation and tourism, public health	State-Level
New York ClimAID Project	New York State Energy Research and Development Authority (Rosenzweig et al. 2011; Horton et al. 2014)[62,63]	Water resources, coastal zones, ecosystems, agriculture, energy, transportation, telecommunications, public health	State-Level

Table 29.1: Selection of Multisector Impacts Modeling Frameworks Since NCA3. Source: adapted from Diaz and Moore 2017.[54]

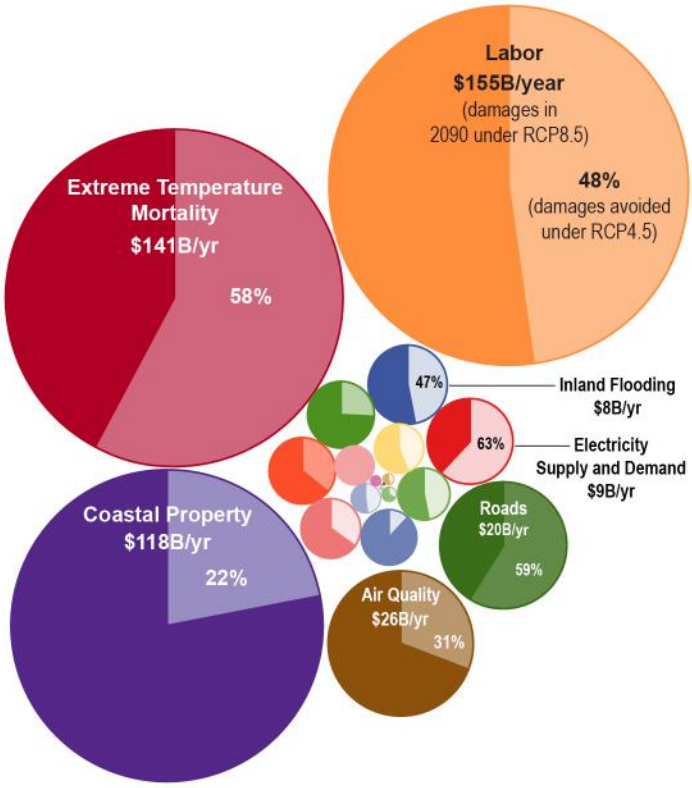
Key Message 2

The Risks of Inaction

In the absence of more significant global mitigation efforts, climate change is projected to impose substantial damages on the U.S. economy, human health, and the environment. Under scenarios with high emissions and limited or no adaptation, annual losses in some sectors are estimated to grow to hundreds of billions of dollars by the end of the century. It is very likely that some physical and ecological impacts will be irreversible for thousands of years, while others will be permanent.

Climate change is projected to significantly affect human health, the economy, and the environment in the United States, particularly in futures with high GHG emissions, such as RCP8.5, and under scenarios with limited or no adaptation (for more on RCPs, see the Scenario Products section of App. 3).[64] Recent findings from multisector modeling frameworks demonstrate substantial and far-reaching changes over the course of the 21st century—and particularly towards the end of the century—with negative consequences for a large majority of sectors. Moreover, the impacts and costs of climate change are already being felt in the United States, and recent extreme weather and climate-related events can now be attributed with increasingly higher confidence to human-caused warming.[65] Impacts associated with human health, such as premature mortality due to extreme temperature and poor air quality, are commonly some of the most economically substantial (Ch. 13: Air Quality; Ch. 14: Human Health).[2,3,4,5] While many sectors face large economic risks from climate change, other impacts can have significant implications for societal or cultural resources.[66,67] Further, some impacts will very likely be irreversible for thousands of years, including those to species, such as corals (Ch. 9: Oceans; Ch. 27: Hawai'i & Pacific Islands),[1,2,68] or those that involve the exceedance of thresholds, such as the effects of ice sheet disintegration on accelerated sea level rise, leading to widespread effects on coastal development lasting thousands of years.[69,70,71] Figure 29.2 shows that climate change is projected to cause damage across nearly all of the sectors analyzed. The conclusion that climate change is projected to result in adverse impacts across most sectors is consistently found in U.S.-focused multisector impact analyses.[2,3,4,5] For sectors where positive effects are observed in some regions or for specific time periods (for example, reduced mortality from extreme cold temperatures or beneficial effects on crop yields), the effects are typically dwarfed by changes happening overall within the sector or at broader scales (for example, comparatively larger increases in mortality from extreme heat or many more crops experiencing adverse effects).[2,3,4,5]

Projected Damages and Potential for Risk Reduction by Sector



Annual Economic Damages in 2090		
Sector	**Annual damages under RCP8.5**	**Damages avoided under RCP4.5**
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Coastal Property◊	$118B	22%
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Inland Flooding	$8B	47%
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Rail◊	$6B	36%
Water Quality	$5B	35%
Coral Reefs	$4B	12%
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Winter Recreation	$2B	107%
Bridges	$1B	48%
Munic. and Industrial Water Supply	$316M	33%
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Alaska Infrastructure◊	$174M	53%
Shellfish*	$23M	57%
Agriculture*	$12M	11%
Aeroallergens*	$1M	57%
Wildfire	−$106M	−134%

Figure 29.2: The total area of each circle represents the projected annual economic damages (in 2015 dollars) under a higher scenario (RCP8.5) in 2090 relative to a no-change scenario. The decrease in damages under a lower scenario (RCP4.5) compared to RCP8.5 is shown in the lighter-shaded area of each circle. Where applicable, sectoral results assume population change over time, which in the case of winter recreation leads to positive effects under RCP4.5, as increased visitors outweigh climate losses. Importantly, many sectoral damages from climate change are not included here, and many of the reported results represent only partial valuations of the total physical damages. See EPA 2017 for ranges surrounding the central estimates presented in the figure; results assume limited or no adaptation.[2] Adaptation was shown to reduce overall damages in sectors identified with the diamond symbol but was not directly modeled in, or relevant to, all sectors. Asterisks denote sectors with annual damages that may not be visible at the given scale. Only one impact (wildfire) shows very small positive effects, owing to projected landscape-scale shifts to vegetation with longer fire return intervals (see Ch. 6: Forests for a discussion on the weight of evidence regarding projections of future wildfire activity). The online version of this figure includes value ranges for numbers in the table. Due to space constraints, the ranges are not included here. Source: adapted from EPA 2017.[2]

Key Message 3

Avoided or Reduced Impacts Due to Mitigation

Many climate change impacts and associated economic damages in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions, though the magnitude and timing of avoided risks vary by sector and region. The effect of near-term emissions mitigation on reducing risks is expected to become apparent by mid-century and grow substantially thereafter.

Many climate change impacts in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in GHG emissions (Figure 29.2). While the difference in climate impact outcomes between different scenarios is more modest through the first half of the century,[6] the effect of mitigation in avoiding climate change impacts typically becomes clear by 2050 and increases substantially in magnitude thereafter.[2,3,4] For some sectors, this creates large projected benefits of mitigation. For example, by the end of the century, reduced climate change under a lower scenario (RCP4.5) compared to a higher one (RCP8.5) avoids (overall) thousands to tens of thousands of deaths per year from extreme temperatures (Ch. 14: Human Health),[2,3,5] hundreds to thousands of deaths per year from poor air quality (Ch. 13: Air Quality),[2,72] and the annual loss of hundreds of millions of labor hours from extreme temperatures.[2,3] When monetized, each of these avoided health impacts represents domestic economic benefits of mitigation on the order of tens to hundreds of billions of dollars per year.[2,3,73] For example, Figure 29.2 shows that reduced emissions under RCP4.5 can avoid approximately 48% (or $75 billion) of the $155 billion in lost wages per year by 2090 due to the effects of extreme temperature on labor (for example, outdoor industries reducing total labor hours during heat waves). Looking at the economy as a whole, mitigation can substantially reduce damages while also narrowing the uncertainty in potential adverse impacts (Figure 29.3).

Many impacts have significant societal or cultural values, such as impacts to freshwater recreational fishing. However, estimating the full value of these changes remains a challenge. Recent studies highlight that climate change can disproportionately affect socially vulnerable communities, with mitigation providing substantial risk reduction for these populations.[3,74,75,76] Some analyses also suggest that findings are sensitive to assumptions regarding adaptive capacity and socioeconomic change.[5,71,77] In general, studies find that reduced damages due to mitigation also reduce the potential level of adaptation needed.[2,78] As for socioeconomic change, increasing population growth can compound the damages occurring from climate change.[4,79] Some studies have shown that impacts can be more sensitive to demographic and economic conditions than to the differences in future climates between the scenarios.[80] See the Scenario Products section of Appendix 3 for more detail on population and land-use scenarios developed for the Fourth National Climate Assessment (NCA4).

For other sectors, such as impacts to coastal development, the effect of mitigation emerges more toward the end of the century due to lags in the response of ice sheets and oceans to warming (Ch. 8: Coastal).[81] This results in smaller relative reductions in risk. For example, while annual damages to coastal property from sea level rise and storm surge, assuming no adaptation, are projected to range in the tens to hundreds of billions of dollars by the end of

Estimates of Direct Economic Damage from Temperature Change

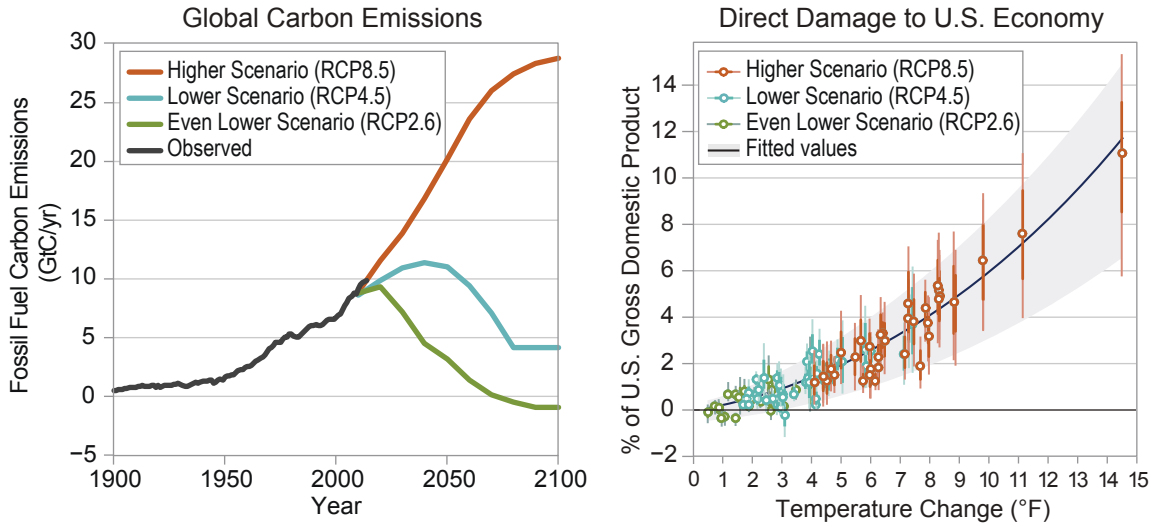

Figure 29.3: The left graph shows the observed and projected changes in fossil fuel and industrial emissions of CO_2 from human activities (emissions from land-use change do not appear in the figure; within the RCPs these emissions are less than 1 GtC per year by 2020 and fall thereafter). The right graph shows projections of direct damage to the current U.S. economy for six impact sectors (agriculture, crime, coasts, energy, heat mortality, and labor) as a function of global average temperature change (represented as average for 2080–2099 compared to 1980–2010). Compared to RCP8.5, lower temperatures due to mitigation under either of the lower scenarios (RCP2.6 or RCP4.5) substantially reduce median damages (dots) to the U.S. economy while also narrowing the uncertainty in potential adverse impacts. Dot-whiskers indicate the uncertainty in direct damages in 2090 (average of 2080–2099) derived from multiple combinations of climate models and forcing scenarios (dot, median; thick line, inner 66% credible interval; thin line, inner 90%). The gray shaded area represents the 90% confidence interval in the fit (black line) to the damage estimates. Damage estimates only capture adaptation to the extent that populations employed them in the historical period. Sources: (left) adapted from Wuebbles et al. 2017; [83] (right) adapted from Hsiang et al. 2017[3] and republished with permission of American Association for the Advancement of Science.

the century under RCP8.5, mitigation under RCP4.5 is projected to avoid less than a quarter of these damages.[2,5,82] However, the avoided impacts beyond 2100 are likely to be larger based on projected trajectories of sea level change.[19,20,27]

The marginal benefit, equivalently the avoided damages, of mitigation can be expressed as the social cost of carbon (SCC). The SCC is a monetized estimate of the long-term climate damages to society from an additional amount of CO_2 emitted and includes impacts that accrue in market sectors such as agriculture, energy services, and coastal resources, as well as nonmarket impacts on human health and ecosystems.[84,85] This metric is used to inform climate risk management decisions at national, state, and corporate levels.[86,87,88,89,90] Notably, estimating the SCC depends on normative social values such as time preference, risk aversion, and equity considerations that can lead to a range of values. In recognition of the ongoing examination about existing approaches to estimating the SCC,[91,92,93] a National Academies of Sciences, Engineering, and Medicine report[94] recommended various improvements to SCC models, including that they 1) be consistent with the current state of scientific knowledge, 2) characterize and quantify key uncertainties, and 3) be clearly documented and reproducible.

Although uncertainties still remain, advancements in climate impacts and economics modeling are increasingly providing new capabilities to quantify future societal effects of climate change. A growing body of studies use and assess statistical relationships between observed socioeconomic outcomes and weather or climate variables to estimate the impacts of climate change (e.g., Müller et al. 2017, Hsiang et

al. 2017 [3,95]). In the United States, in particular, the rise of big data (large volumes of data brought about via the digital age) and advanced computational power offer potential improvements to study climate impacts in many sectors like agriculture, energy, and health, including previously omitted sectors such as crime, conflict, political turnover, and labor productivity. Parallel advancements in high-resolution integrated assessment models (those that jointly simulate changes in physical and socioeconomic systems), as well as process-based sectoral models (those with detailed representations of changes in a single sector), enable impact projections with increased regional specificity, which across the modeling frameworks shown in Table 29.1 reveal complex spatial patterns of impacts for many sectors. For example, this spatial variability is consistently observed in the agriculture sector,[2,5,96,97] where the large number of domestic crops and growing regions respond to changes in climate and atmospheric CO_2 concentrations in differing ways. As such, the benefits of mitigation for agriculture can vary substantially across regions of the United States and summing regional results into national estimates can obscure important effects at the local level.

Key Message 4

Interactions Between Mitigation and Adaptation

Interactions between mitigation and adaptation are complex and can lead to benefits, but they also have the potential for adverse consequences. Adaptation can complement mitigation to substantially reduce exposure and vulnerability to climate change in some sectors. This complementarity is especially important given that a certain degree of climate change due to past and present emissions is unavoidable.

The reduction of climate change risk due to mitigation also depends on assumptions about how adaptation changes the exposure and vulnerability of the population (Ch. 28: Adaptation). For example, recent studies have found that adaptation can substantially reduce climate damages in a number of sectors in both the higher (RCP8.5) and lower (RCP4.5) scenarios.[2,5] Damages to infrastructure, such as road and rail networks, are particularly sensitive to adaptation assumptions, with proactive measures (such as planned maintenance and repairs that account for future climate risks) estimated to be able to reduce damages by large fractions. More than half of damages to coastal property are estimated to be avoidable through well-timed adaptation measures, such as shoreline protection and beach replenishment.[2,5,196] In the health sector, accounting for possible physiological adaptation (acclimatization) to higher temperatures and for increased air conditioning use reduced estimated mortality by half,[2,5] a finding supported by other analyses of mortality from extreme heat.[99,100] However, adaptation can require large up-front costs and long-term commitments for maintenance (Ch. 28: Adaptation), and uncertainty exists in some sectors regarding the applicability and effectiveness of adaptation in reducing risk.[101]

Broadly, quantifying the potential effect of adaptation on impacts remains a research challenge (see the "Direction for Future Research" section) (see also Ch. 17: Complex Systems).[102] Because society is already committed to a certain amount of future climate change due to past and present emissions and because mitigation activities cannot avoid all climate-related risks, mitigation and adaptation activities can be considered complementary strategies.[196,103,104,105]

Adaptation and mitigation strategies can also interact, with the potential for benefits

and/or adverse consequences.[106] An iterative risk-management approach for assessing and modifying these strategies as experience is gained can be advantageous (Ch. 28: Adaptation). Benefits occur when mitigation strategies make adaptation easier (or vice versa). For example, by reducing climate change and its subsequent effects on the water cycle, mitigation has been projected to reduce water shortages in most river basins of the United States, making adaptation to hydrologic impacts more manageable.[107] Also, carbon sequestration through reforestation and/or other protective measures can promote forest ecosystem services (including reduced flood risk), provide habitat for otherwise vulnerable species, or abate urban heat islands. Carbon sequestration measures in agriculture can reduce erosion and runoff, reducing vulnerability to extreme precipitation. Agricultural adaptation strategies that increase yields (such as altering crop varieties, irrigation practices, and fertilizer application), particularly in already high-yielding regions including North America, can have mitigation benefits (Ch. 10: Ag & Rural).[108] First, higher productivity lessens the need for clearing new land for production, thereby reducing associated emissions.[109] Second, these strategies counteract yield losses due to climate change,[2,110,111] which could enhance the ability to produce bioenergy crops or make additional land available for carbon sequestration.

In buildings and industrial facilities, adaptation measures such as investments in energy efficiency (for example, through efficient building materials) would reduce building energy demand (and therefore emissions), as well as lessen the impacts of extreme heat events.[112,113]

Adaptation and mitigation can also interact negatively. For example, if mitigation strategies include large-scale use of bioenergy crops to produce low-carbon energy, higher irrigation demand can lead to an increase in water stress that more than offsets the benefits of lessened climate change.[114] Similarly, mitigation approaches such as afforestation (the establishment of a forest where no previous tree cover existed) and concentrated solar power would increase demand for water and land.[115] Likewise, some adaptation measures such as irrigation, desalination, and air conditioning are energy intensive and would lead to increased emissions or create greater demands for clean energy. Higher air conditioning demands are projected to increase annual average and peak demands for electricity, putting added stress on an electrical grid that is already vulnerable to the effects of climate change (Ch. 4: Energy, KM 1).[2,116,117] Meeting these higher demands becomes more challenging as higher temperatures reduce the peak capacity of thermal generation technologies and lower peak transmission capacity.[118] In addition, complications are expected to arise when climate change impacts occur simultaneously and undermine adaptation measures, such as when a severe storm disrupts power over an extended time of intense heat, which can nullify the benefits of air conditioning adaptation.

Box 29.2: Co-Effects of Mitigation Actions

Recent scientific studies suggest that considering the indirect effects of mitigation can significantly reduce or eliminate the potential costs associated with cutting GHG emissions. This is due to the presence of co-benefits, often immediate, associated with emissions reductions, such as improving air quality and public health. There is now a large body of scientific literature evaluating 1) the health co-benefits of mitigation actions, [5,119,120,121,122,123,124,125] 2) improvement to crop yields,[126,127] and 3) a reduction in the probability of occurrence of extreme weather and climate-related events over the next decades that would otherwise occur with unabated emissions.[29] In transportation, for example, switching away from petroleum to potentially lower GHG fuels, such as electricity and hydrogen, is projected to reduce local air pollution. In California, drastic GHG emissions reductions have been estimated to substantially improve air quality and reduce local particulate matter emissions associated with freight transport that disproportionately impact disadvantaged communities.[128,129] Decarbonization of the energy system is also expected to increase energy security by increasing reliance on sources of energy that are produced domestically.[130,131]

At the same time, mitigation actions can have potential adverse effects, such as impacts to the cost of food and biodiversity loss due to the increased use of energy from biomass.[132,133] For this reason, it is more appropriate to use the term co-effects to refer to both benefits and costs associated with efforts to reduce GHG emissions.[123] The co-effects of investments in GHG emissions reductions generally occur in the near term, whereas the benefits of reducing GHG emissions will likely be mostly realized over longer timescales.

Box 29.3: Reducing Risk Through Climate Intervention

Climate intervention techniques (or geoengineering) are aimed at limiting global or regional temperature increase by affecting net radiative forcing through means other than emissions reductions (for a more detailed discussion see DeAngelo et al. 2017 [9]).There are two broad categories of climate intervention techniques. One is carbon dioxide removal (CDR), which would reduce atmospheric CO_2 concentrations by changing land-use and management practices to store carbon in plants, trees, and soils; increasing ocean carbon storage through biological or chemical means; capturing atmospheric CO_2 through engineered chemical reactions and storing it in geologic reservoirs; or converting terrestrial biomass into energy while capturing and storing the CO_2.[16] The second is solar radiation management (SRM), which would increase Earth's regional and/or global reflectivity by, for example, injecting sulfur gases or other substances into the stratosphere or brightening marine clouds. CDR is estimated to have long implementation times, and while costs (and their uncertainties) range widely across different measures,[134] it is estimated to be expensive at scale.[10] Nonetheless, large-scale CDR can be competitive with more traditional GHG mitigation options when substantial mitigation is required, and therefore it is an element of many scenarios that feature deep emissions reductions or negative emissions. Its climate benefits are likely to be similar to those from emissions reductions since both strategies act through reduced atmospheric concentrations of GHGs. Studies point to the risks of reaching the limits of available land, water, or biogeochemical requirements of biomass-based approaches at scale sufficient to offset large emissions.[13,16,99,135,136] In contrast to CDR, SRM strategies are estimated to be relatively inexpensive and realize climate benefits within a few years. They could be targeted at regional as well as global temperature modification[137] and could be combined with mitigation to limit the rate or the peak magnitude of warming. However, SRM effects on other outcomes, including precipitation patterns, light availability, and atmospheric circulation, are less well understood. In addition, SRM would not reduce risks from increasing atmospheric CO_2 concentra-

Box 29.3: Reducing Risk Through Climate Intervention, *continued*

tions such as ocean acidification.[138,139] Moreover, a sudden cessation of large-scale SRM activities could lead to very rapid climate changes, although a gradual phaseout of SRM as emissions reductions and CDR are phased in could avoid these abrupt changes. As concluded in Chapter 14 of the *Climate Science Special Report*, "Further assessments of the technical feasibilities, costs, risks, co-benefits, and governance challenges of climate intervention or geoengineering strategies, which are as-yet unproven at scale, are a necessary step before judgments about the benefits and risks of these approaches can be made with high confidence."[9]

Direction for Future Research

Coordinated Impacts Modeling Analyses

Multisector impacts modeling frameworks can systematically address specific mitigation and adaptation research needs of the users of the National Climate Assessment. Improved coordination amongst multidisciplinary impact modeling teams could be very effective in informing future climate assessments.

The recent multisector impacts modeling frameworks described above have demonstrated several key advantages for producing policy-relevant information regarding the potential for mitigation to reduce climate change impacts. First, the use of internally consistent scenarios and assumptions in quantifying a broad range of impacts produces comparable estimates across sectors, regions, and time. Second, these frameworks can simulate specific mitigation and adaptation scenarios to investigate the multisector effectiveness of these actions in reducing risk over time. Third, these frameworks can be designed to systematically account for key dimensions of uncertainty along the causal chain—a difficult task when assessing uncoordinated studies from the literature, each with its own choices of scenarios and assumptions.

Advancements to Address Research Needs from the Third National Climate Assessment

While not an exact analog to this chapter, the Third National Climate Assessment (NCA3)[140] included a Research Needs chapter as part of the Response Strategies section that recommended five research goals: 1) improve understanding of the climate system and its drivers, 2) improve understanding of climate impacts and vulnerability, 3) increase understanding of adaptation pathways, 4) identify the mitigation options that reduce the risk of longer-term climate change, and 5) improve decision support and integrated assessment.[141] Several of these topics have seen substantial advancements since publication of NCA3, informing our understanding of avoided climate risks. For example, research findings related to climate system drivers and the characterization of uncertainty have helped to differentiate the physical and economic outcomes along alternative mitigation pathways.[3,20,30] Enormous growth in impacts, adaptation, and vulnerability (IAV) research has enabled more robust quantification of the relative impacts (avoided damages) corresponding to different climate outcomes. However, challenges remain in accounting for the reduced risks and impacts associated with nonlinearities in the climate system, including tipping points such as destabilization of the West Antarctic ice sheet or rapid methane release from thawing permafrost.[22,98,142,143] Mitigation options continue to be studied to better understand their potential role in meeting different climate targets, and while many low-emitting or renewable technologies have seen rapid penetration, other strategies involving negative-emissions technologies have prompted caution due to the challenges of

achieving widespread deployment at low cost. Adaptation pathways are better understood but continue to be a source of uncertainty related to understanding climate risk and local adaptation decision-making processes. Decision support for climate risk management, especially under uncertainty, is an area of active research,[144,145] and despite the limitations of integrated assessment models,[146,147] they offer useful insights for decision-makers.[148]

Remaining Knowledge Gaps

Despite ongoing progress, this assessment finds that significant knowledge gaps remain in many of the research goals and foundational crosscutting capabilities identified in NCA3. Going forward, it will be critically important to reduce uncertainties under different mitigation scenarios in 1) avoided sectoral impacts, such as agriculture and health, and 2) the capacity for adaptation to reduce impacts. Gaps in information on social vulnerability and exposure continue to hamper progress on disaster risk reduction associated with climate impacts.[51] Directions for future research in the climate science and impacts field include improved understanding of the avoided/increased risk of thresholds, tipping points, or irreversible outcomes (see Kopp et al. 2017[22]). Specific examples deserving further study include marine ice sheet instability and transformation of specific terrestrial carbon sinks into sources of greenhouse gas emissions.[149,150]

Gaps remain in quantifying combined impacts and natural feedbacks. For example, coral reef health includes combined stress/relief from changes in local activities (for example, agricultural and other nutrient runoff and fishery management), ocean acidification, ocean temperature, and the ability of coral species to adapt to changing conditions or repeated extreme events.[151,152] Additional knowledge gaps include an understanding of how mitigation and adaptation actions affect climate outcomes due to interactions in the coupled human–earth system.[142,153]

Interdisciplinary collaboration can play a critical role in addressing these knowledge gaps (such as coordinating a research plan across physical, natural, and social sciences).[52,154] Combining advances in scientific understanding of the climate system with scenarios to explore socioeconomic responses is expected to lead to an improved understanding of the coupled human–earth system that can better support effective adaptation and mitigation responses. Barriers to implementation arise from data limits (for example, the need for long-term observational records), as well as computational limits that increase model uncertainties.[53]

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Traceable Accounts

Process Description

The scope for this chapter was determined by the federal Fourth National Climate Assessment (NCA4) Steering Committee, which is made up of representatives from the U.S. Global Change Research Program (USGCRP) member agencies (see App. 1: Process for more information regarding the Steering Committee). The scope was also informed by research needs identified in the Third National Climate Assessment (NCA3) and in subsequent gap analyses.[155] Prospective authors were nominated by their respective agency, university, organization, or peers. All prospective authors were interviewed with respect to their qualifications and expertise. Authors were selected to represent the diverse perspectives relevant to mitigation, with the final team providing perspectives from federal and state agencies, nonfederal climate research organizations, and the private sector. The author team sought public input on the chapter scope and outline through a webinar and during presentations at conferences and workshops.

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors during extensive teleconferences, workshops, and email exchanges. These discussions were informed by the results of a comprehensive literature review, including the research focused on estimating the avoided or reduced risks of climate change. The authors considered inputs submitted by the public, stakeholders, and federal agencies and improved the chapter based on rounds of review by the public, National Academies of Sciences, Engineering, and Medicine, and federal agencies. The author team also engaged in targeted consultations during multiple exchanges with contributing authors from other chapters of this assessment, as well as authors of the *Climate Science Special Report* (CSSR). For additional information on the overall report process, see Appendix 1: Process.

Key Message 1

Mitigation-Related Activities Within the United States

Mitigation-related activities are taking place across the United States at the federal, state, and local levels as well as in the private sector (*very high confidence*). Since the Third National Climate Assessment, a growing number of states, cities, and businesses have pursued or deepened initiatives aimed at reducing emissions (*very high confidence*).

Description of evidence base

Since NCA3, state, local, and tribal entities have announced new or enhanced efforts to reduce greenhouse gas (GHG) emissions. While some policies with emissions co-benefits have been eliminated, on net there has been an increase in initiatives aimed at reducing emissions. Figure 29.1 includes several types of state-level efforts and is sourced from Figure ES-3 of the America's Pledge Phase 1 report, the most comprehensive listing of efforts across sectors currently available. The underlying state information is sourced from the U.S. Department of Energy, Appliance Standards Awareness Project, Open Energy Information, Rethink Food Waste Through Economics and Data, World Resources Institute, State of New York, California Air Resources Board, University of Minnesota, Land Trust Alliance, and the U.S. Forest Service.

U.S. state and local carbon pricing programs have increased in number since NCA3.[156] The Regional Greenhouse Gas Initiative has expanded the depth of emissions reductions activities and is considering adding transportation to their scope. California's cap and trade program started in 2012 and expanded by linking to Quebec and Ontario in 2017. Emissions trading systems are scheduled in Massachusetts and under consideration in Virginia.[156]

U.S. states have both mandatory and voluntary programs that vary in stringency and impact. For example, 29 states, Washington, DC, and 3 territories have Renewable Portfolio Standards (RPS; https://energy.gov/eere/slsc/renewable-portfolio-standards-resources), which require some portion of electricity to be sourced from renewable energy; while 8 states and 1 territory have voluntary renewable portfolio goals.[42,45] Likewise, 20 states have mandatory statewide Energy Efficiency Resource Standards (EERS; https://energy.gov/eere/slsc/energy-efficiency-resource-standards-resources), and 8 states have energy efficiency goals.[42] While the number of states with RPS and EERS policies remains similar to that during NCA3, emissions reductions associated with the impact of these policies have and are projected to increase.[157] In 2013, 8 states initiated an effort to coordinate implementation of their state zero-emission vehicle programs and have since taken a wide range of actions.[158]

Federal budget levels for activities that have reduced GHG have remained steady over recent years. There is uncertainty around the implementation of federal initiatives, in part owing to the implementation of Executive Order 13783.[40,159] Federal energy-related research and development have several co-benefits, including reduced emissions.[15]

U.S. companies that report through the Carbon Disclosure Project increasingly (although not comprehensively) reported board-level oversight on climate issues, which rose from 50% in 2011 to 71% in 2017. Likewise, 59 U.S. companies recently committed to set science-based emissions reduction targets.[46] U.S. businesses are increasingly pricing carbon.[46,160] Corporate procurement of utility-scale solar has grown by an order of magnitude since 2014.[47]

As indicated in the Education Institutions Reporting Database, a growing number of universities have made emissions reduction commitments or deepened existing commitments[161] as well as publicized the progress on their efforts.[162]

Major uncertainties

Figure 29.1 shows a count of each type of 30 measures across 6 categories, but it does not explore the relative stringency or emissions impact of the measures. The size, scope, time frame, and enforceability of the measures vary across states. Some state efforts and the majority of city efforts are voluntary, and therefore standards for reporting are heterogeneous. Efforts are underway to provide a rigorous accounting of the cumulative scale of these initiatives. Data collection through the America's Pledge effort is an ongoing, iterative process and, by necessity, involves aggregating different measures into categories. Historically, state, local, and corporate policies change on different cycles.

Description of confidence and likelihood

There is *very high confidence* that state, local, and private entities are increasingly taking, or are committed to taking, GHG mitigation action. Public statements and collated indices show an

upward trend in the number of commitments, as well as the breadth and depth of commitments over the past five years.

Key Message 2

The Risks of Inaction

In the absence of more significant global mitigation efforts, climate change is projected to impose substantial damages on the U.S. economy, human health, and the environment (*very high confidence*). Under scenarios with high emissions and limited or no adaptation, annual losses in some sectors are estimated to grow to hundreds of billions of dollars by the end of the century (*high confidence*). It is very likely that some physical and ecological impacts will be irreversible for thousands of years, while others will be permanent (*very high confidence*).

Description of evidence base

Recent scientific and economic advances are improving the ability to understand and quantify the physical and economic impacts of climate change in the United States, including how those risks can be avoided or reduced through large-scale GHG mitigation. While the projected impacts of climate change across sectors and regions are well documented throughout this assessment, several multisector modeling projects are enabling the comparison of effects through the use of consistent scenarios and assumptions.[2,3,4,5] A well-recognized conclusion from the literature produced by these projects is that climate change is projected to adversely affect the U.S. economy, human health, and the environment, each of which is further detailed below. These estimated damages increase over time, especially under a higher scenario (RCP8.5). For sectors where positive effects are observed in some regions or for specific time periods (for example, reduced mortality from extreme cold temperatures or beneficial effects on crop yields), the effects are typically dwarfed by changes happening overall within the sector or at broader scales (for example, comparatively larger increases in mortality from extreme heat or many more crops experiencing adverse effects).[2,3,4,5] In Figure 29.2, wildfire is the only sector showing positive effects, a result driven in this particular study by projected shifts to vegetation with longer fire return intervals.[2] However, it is important to note that the analysis underlying this result did not quantify the broader economic effects associated with these vegetative shifts, including ecosystem disruption and changes to ecosystem services. See Chapter 6: Forests for a discussion on the weight of evidence regarding projections of future wildfire activity, which generally show increases in annual area burned over time. See Chapter 25: Southwest for a discussion on aridification toward the end of this century under high emissions.

There is robust and consistent evidence that climate change is projected to adversely affect many components of the U.S. economy. Increasing temperatures, sea level rise, and changes in extreme events are projected to affect the built environment, including roads, bridges, railways, and coastal development. For example, coastal high tide flooding is projected to significantly increase the hours of delay for vehicles.[163] Annual damages to coastal property from sea level rise and storm surge, assuming no adaptation, are projected to range in the tens to hundreds of billions of dollars by the end of the century under RCP8.5 (Ch. 8: Coastal).[2,5] Projected annual repair costs in order for roads, bridges, and railways to maintain levels of service in light of climate change range in

the billions to tens of billions of dollars under RCP8.5.[2,164] Numerous studies suggest that regional economies can also be at risk, especially when they are tied to environmental resources or ecosystem services that are particularly vulnerable to climate change. For example, projected declines in coral reef-based recreation[152,165,166] would lead to decreases in tourism revenue; shorter seasons for winter recreation would likely lead to the closure of ski areas and resorts;[167,168,169,170] and increased risks of harmful algal blooms can limit reservoir recreation (Ch. 3: Water).[171,172]

An increasing body of literature indicates that impacts to human health are likely to have some of the largest effects on the economy. Studies consistently indicate that climate-driven changes to morbidity and mortality can be substantial.[72,100,173,174,175,176] In some sectors, the value of health damages is estimated to reach hundreds of billions of dollars per year under RCP8.5 by the end of the century. A large fraction of total health damages is due to mortality, quantified using the Value of a Statistical Life (VSL) approach based on standard VSL values used in federal government regulatory analysis.[177] For example, annual damages associated with extreme temperature-related deaths are estimated at $140 billion by the end of the century under RCP8.5, while lost wages from extreme temperatures, especially for outdoor industries, are projected at $160 billion per year by 2090.[2] Adaptive actions, including physiological adaptation and increased availability of air conditioning, are projected to reduce extreme temperature mortality by approximately half; however, the implementation costs of those adaptations were not estimated. Although less studied compared to the research on the direct effects of temperature on health, climate-driven impacts to air quality[72,178] and aeroallergens[173,179] are also projected to have large economic effects, due to increases in medical expenditures (such as emergency room visits) and premature mortality (Ch. 13: Air Quality).

Multiple lines of research have also shown that some climate change impacts will very likely be irreversible for thousands of years. For some species, the rate and magnitude of climate change projected for the 21st century is projected to increase the risk of extinction or extirpation (local-scale extinction) from the United States.[180,181,182,183] Coral reefs, coldwater fish, and high-elevation species are particularly vulnerable (Ch. 9: Oceans; Ch. 7: Ecosystems). The rapid and widespread climate changes occurring in the Arctic and Antarctic are leading to the loss of mountain glaciers and shrinking continental ice sheets.[69,184] The contribution of this land ice volume to the rate of global sea level rise is projected to affect U.S. coastlines for centuries (Ch. 8: Coastal).[19,30,185]

Major uncertainties

This Key Message reflects consideration of the findings of several recent multisector modeling projects (e.g., Hsiang et al. 2017, O'Neill et al. 2017, EPA 2017, Houser et al. 2015 [2,3,4,5]) released since NCA3. Despite these improvements to quantify the physical and economic impacts of climate change across sectors, uncertainty exists regarding the ultimate timing and magnitude of changes, particularly at local to regional scales. The sources of uncertainty vary by sector and the modeling approaches applied. Each approach also varies in its capacity to measure the ability of adaptation to reduce vulnerability, exposure, and risk. While the coverage of impacts has improved with recent advancements in the science, many important climate change effects remain unstudied, as do the interactions between sectors (Ch. 17: Complex Systems).[85] Finally, as climate conditions pass further outside the natural variability experienced over past several millennia, the odds of crossing thresholds or tipping points (such as the loss of Arctic summer sea ice) increase, though these thresholds are not well represented in current models.[22,142]

Description of confidence and likelihood

There is *very high confidence* that climate change is projected to substantially affect American livelihoods and well-being in the future compared to a future without climate change. The evidence supporting this conclusion is based on agreement across a large number of studies analyzing impacts across a multitude of sectors, scenarios, and regions. The literature clearly indicates that the adverse impacts of climate change are projected to substantially outweigh the positive effects. Although important uncertainties exist that affect our understanding of the timing and magnitude of some impacts, there is *very high confidence* that some effects will very likely lead to changes that are irreversible on human timescales.

Key Message 3

Avoided or Reduced Impacts Due to Mitigation

Many climate change impacts and associated economic damages in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions, though the magnitude and timing of avoided risks vary by sector and region (*very high confidence*). The effect of near-term emissions mitigation on reducing risks is expected to become apparent by mid-century and grow substantially thereafter (*very high confidence*).

Description of evidence base

There are multiple lines of research and literature available to characterize the effect of large-scale GHG mitigation in avoiding or reducing the long-term risks of climate change in the United States. Recent multisector impacts modeling projects, all of which feature consistent sets of scenarios and assumptions across analyses, provide improved capabilities to compare impacts across sectors and regions, including the effect of global GHG mitigation in avoiding or reducing risks.[2,3,4,5] The results of these coordinated modeling projects consistently show reductions in impacts across sectors due to large-scale mitigation. For most sectors, this effect of mitigation typically becomes clear by mid-century and increases substantially in magnitude thereafter. In some sectors, mitigation can provide large benefits. For example, by the end of the century, reduced climate change under a lower scenario (RCP4.5) compared to a higher one (RCP8.5) avoids (on net, and absent additional risk reduction through adaptation) thousands to tens of thousands of deaths per year from extreme temperatures,[2,5] hundreds to thousands of deaths per year from poor air quality,[2,72] and the loss of hundreds of millions of labor hours.[2,3,5]

Beyond these multisector modeling projects, an extensive literature of sector-specific studies compares impacts in the United States under alternative scenarios. A careful review of these studies, especially those published since the Third National Climate Assessment, finds strong and consistent support for the conclusion that global GHG mitigation can avoid or reduce the long-term risks of climate change in the United States. For example, mitigation is projected to reduce the risk of adverse impacts associated with extreme weather events,[29,186] temperature-related health effects,[99,100,175] agricultural yields,[187,188,189] and wildfires.[73,190,191]

The finding that the magnitude and timing of avoided risks vary by sector and region, as well as due to changes in socioeconomics and adaptive capacity, is consistently supported by the broad literature base of multisector analyses (e.g., Hsiang et al. 2017, O'Neill et al. 2017, EPA 2017, Houser

et al. 2015[2,3,4,5]) and focused sector studies (e.g., Melvin et al. 2016, Neumann et al. 2014[71,77]). Complex spatial patterns of avoided risks are commonly observed across sectors, including for human health effects (e.g., Fann et al. 2015, Sarofim et al. 2016 [100,178]), agriculture (e.g., Beach et al. 2015 [192]), and water resources (e.g., Chapra et al. 2017, Wobus et al. 2017, EPA 2013[167,171,193]).

The weight of evidence among studies in the literature indicates that the difference in climate impact outcomes between different scenarios is more modest through the first half of the century,[2,4,5,9] as the human-forced response may not yet have emerged from the noise of natural climate variability.[6] In evaluating and quantifying multisector impacts across alternative scenarios, the literature generally shows that the effect of near-term mitigation in avoiding damages increases substantially in magnitude after 2050.[2,4,5] For example, mitigation under RCP4.5 is projected to reduce the number of premature deaths and lost labor hours from extreme temperatures by 24% and 21% (respectively) by 2050, and 58% and 48% by 2090.[2] For coastal impacts, where inertia in the climate system leads to smaller differences in rates of sea level rise across scenarios, the effects of near-term mitigation only become evident toward the end of the century (Ch. 8: Coastal).[2,5,19]

Major uncertainties

Quantifying the multisector impacts of climate change involves a number of analytic steps, each of which has its own potential sources of uncertainty. The timing and magnitude of projected future climate change are uncertain due to the ambiguity introduced by human choices, natural variability, and scientific uncertainty, which includes uncertainty in both scientific modeling and climate sensitivity. One of the most prominent sources involves the projection of climate change at a regional level, which can vary based on assumptions about climate sensitivity, natural variability, and the use of any one particular climate model. Advancements in the ability of climate models to resolve key aspects of atmospheric circulation, improved statistical and dynamic downscaling procedures, and the use of multiple ensemble members in impact analyses have all increased the robustness of potential climate changes that drive impact estimates described in the recent literature. However, key uncertainties and challenges remain, including the structural differences between sectoral impact models, the ability to simulate future impacts at fine spatial and temporal resolutions, and insufficient approaches to quantify the economic value of changes in nonmarket goods and services.[85] In addition, the literature on economic damages of climate change in the United States is incomplete in coverage, and additional research is needed to better reflect future socioeconomic change, including the ability of adaptation to reduce risk.

Description of confidence and likelihood

There is *very high confidence* that large-scale reductions in GHG emissions throughout the 21st century are projected to reduce the level of climate change projected to occur in the United States, along with the adverse impacts affecting human health and the environment. Across the literature, there are limited instances where mitigation, compared to a higher emissions scenario, does not provide a net beneficial outcome for the United States. While the content of this chapter is primarily focused on the 21st century, confidence in the ability of mitigation to avoid or reduce impacts improves when considering impacts beyond 2100.

Key Message 4

Interactions Between Mitigation and Adaptation

Interactions between mitigation and adaptation are complex and can lead to benefits, but they also have the potential for adverse consequences (*very high confidence*). Adaptation can complement mitigation to substantially reduce exposure and vulnerability to climate change in some sectors (*very high confidence*). This complementarity is especially important given that a certain degree of climate change due to past and present emissions is unavoidable (*very high confidence*).

Description of evidence base

Global-scale reductions in GHG emissions are projected to reduce many of the risks posed by climate change. However, Americans are already experiencing, and will continue to experience, impacts that have already been committed to because of past and present emissions.[5,9] In addition, multisector modeling frameworks demonstrate that mitigation is unlikely to completely avoid the adverse impacts of climate change.[2,3,4,5,27] These factors will likely necessitate widespread adaptation to climate change (Ch. 28: Adaptation); an expanding literature consistently indicates potential for the reduction of long-term risks and economic damages of climate change.[2,4,5,194] However, it is important to note that adaptation can require large up-front costs and long-term commitments for maintenance (Ch. 28: Adaptation), and uncertainty exists in some sectors regarding the applicability and effectiveness of adaptation in reducing risk.[101]

Because of adaptation's ability to reduce risk in ways that mitigation cannot, and vice versa, the weight of the evidence shows that the two strategies can act as complements. Several recent studies jointly model the effects of mitigation and adaptation in reducing overall risk to the impacts of climate change in the United States, focusing on infrastructure (e.g., Larsen et al. 2017, Melvin et al. 2016, Neumann et al. 2014 [71,77,195]) and agriculture (e.g., Kaye and Quemada 2017, Challinor et al. 2014, Lobell et al. 2013 [108,109,111]). Exploration of this mitigation and adaptation nexus is also advancing in the health sector, with both mitigation and adaptation (such as behavioral changes or physiological acclimatization) being projected to reduce deaths from extreme temperatures[100] in both the higher and lower emissions scenarios that are the focus of this chapter. Similarly, energy efficiency investments are reducing GHG emissions and operating costs and improving resilience to future power interruptions from extreme weather events (Ch. 14: Human Health). While more studies exploring the joint effects of mitigation and adaptation are needed, recent literature finds that combined mitigation and adaptation actions can substantially reduce the risks posed by climate change in several sectors.[2,103,104] However, several studies highlight that mitigation and adaptation can also interact negatively. While these studies are more limited in the literature, sectors exhibiting potential negative co-effects from mitigation and adaptation include the bioenergy–water resource nexus[114] and changes in electricity demand and supply in response to increased use of air conditioning.[2,117]

Major uncertainties

It is well understood that adaptation will likely reduce climate risks and that adaptation and mitigation interact. However, there are uncertainties regarding the magnitude, timing, and regional/sectoral distribution of these effects. Developing a full understanding of the interaction between

mitigation and adaptation, with detailed accounting of potential positive and negative co-effects, is an important research objective that is only beginning to be explored in the detail necessary to inform effective implementation of these policies. Quantifying the effectiveness of adaptation requires detailed analyses regarding the timing and magnitude of how climate is projected to affect people living in the United States and their natural and built environments. As such, the uncertainties described under Key Messages 1 and 2 are also relevant here. Further, uncertainty exists regarding the effectiveness of adaptation measures in improving resilience to climate impacts. For some sectors, such as coastal development, protection measures (for example, elevating structures) have been well studied and implemented to reduce risk. However, the effectiveness of adaptation in other sectors, such as the physiological response to more intense heat waves, is only beginning to be understood.

Description of confidence and likelihood

There is *very high confidence* that the dual strategies of mitigation and adaptation being taken at national, regional, and local levels provide complementary opportunities to reduce the risks posed by climate change. Studies consistently find that adaptation would be particularly important for impacts occurring over the next several decades, a time period in which the effects of large-scale mitigation would not yet be easily recognizable. However, further analysis is needed to help resolve uncertainties regarding the timing and magnitude of adaptation, including the potential positive and negative co-effects with mitigation.

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A1 Appendix 1. Report Development Process

Assessments are essential tools for linking science and decision-making. The Global Change Research Act (GCRA) of 1990[1] charged the U.S. Global Change Research Program (USGCRP) with a legal mandate to conduct a scientific assessment on the effects of global change not less frequently than every four years; the third and most recent National Climate Assessment (NCA) was released in May 2014.[2]

NCA Goal and Vision

In fulfillment of this mandate and in support of its Strategic Plan,[3,4] USGCRP coordinated this Fourth National Climate Assessment (NCA4), which focuses on advancing our collective understanding of how climate change poses risks to things of value to society. Much of the NCA4 process builds on the Third National Climate Assessment (NCA3),[2] and thus much of this process description is derived from that of NCA3. However, several changes have been made in light of lessons learned through an external evaluation of NCA3 (see "What Has Happened Since the Last National Climate Assessment?" in Ch. 1: Overview).[6] Some of those changes are discussed in greater detail in this appendix.

The vision for the NCA is to continue advancing an inclusive, broad-based, and sustained process for assessing and communicating scientific knowledge of the impacts, risks, and vulnerabilities associated with a changing global climate and to support informed decision-making across the United States.

Legislative Foundations

U.S. Global Change Research Program

Founded by Presidential Initiative in 1989, the U.S. Global Change Research Program aims to build a knowledge base that informs human responses to climate and global change through coordinated and integrated federal programs of research, education, communication, and decision support.

The Global Change Research Act of 1990 cemented into law what was started by President Ronald Reagan. USGCRP is mandated to develop and coordinate "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict and respond to human-induced and natural processes of global change."[1]

National Climate Assessment

Section 106 of the GCRA requires a report to the President and the Congress not less frequently than every four years that 1) integrates, evaluates, and interprets the findings of the USGCRP; 2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and 3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

Institutional Foundations

U.S. Global Change Research Program

USGCRP is a confederation of 13 federal departments and agencies (Figure A1.1) that supports the largest investment in climate and global change research in the world. USGCRP coordinates research activities across agencies, produces the congressionally mandated products, and provides data and products to inform decisions. USGCRP's Strategic Plan, released in 2012 and updated in 2017, focuses on four major goals: advance science, inform decisions, conduct sustained assessments, and communicate and educate.[3,4] The USGCRP agencies maintain and develop observations, monitoring assets, data management, analysis of data products, and modeling capabilities that support the Nation's response to global change. The agencies that make up USGCRP are:

Department of Agriculture (USDA)

Department of Commerce (DOC)

Department of Defense (DOD)

Department of Energy (DOE)

Department of Health and Human Services (HHS)

Department of the Interior (DOI)

Department of State (DOS)

Department of Transportation (DOT)

Environmental Protection Agency (EPA)

National Aeronautics and Space Administration (NASA)

National Science Foundation (NSF)

The Smithsonian Institution (SI)

U.S. Agency for International Development (USAID)

The Subcommittee on Global Change Research (SGCR) oversees USGCRP's activities. The SGCR operates under the direction of the National Science and Technology Council's Committee on the Environment (CoE) and is overseen by the White House Office of Science and Technology Policy (OSTP). The SGCR coordinates interagency activities through the USGCRP National Coordination Office (NCO) and informal interagency working groups (IWGs).

National Climate Assessment Components

The **NCA4 Federal Steering Committee (NCA4 SC)** consists of representatives of the USGCRP member agencies, listed above. In consultation with the SGCR, the NCA4 SC was responsible for the development, production, and content of NCA4 (Figures A1.2, A1.3). The NCA4 SC was charged with overseeing development of technical content and with conducting high-level scoping of the report to ensure coherence, relevance, and responsiveness to the Global Change Research Act and the USGCRP Strategic Plan. The NCA4 SC was also responsible for ensuring that the report development process was robust and that it adhered to the principles of engagement and transparency that are crucial to the process

Figure A1.1: Logos of the 13 agencies that make up USGCRP.

of conducting sustained assessments. In some ways, the NCA4 SC served in a similar capacity to the National Climate Assessment and Development Advisory Committee (NCADAC) during the course of NCA3 development. The NCA4 SC met weekly during the early stages of the report's development before moving towards a more quasi-monthly meeting schedule once writing began in earnest.

The **Administrative Agency** of NCA4 was the National Oceanic and Atmospheric Administration (NOAA). In this role, NOAA was responsible for providing oversight and access to federal resources for the NCA, including (but not limited to) leadership on the NCA4 SC, management of Federal Register Notices, and dedicated funding of external engagement activities, among other supportive activities.

Agency Chapter Leads (ACLs) oversaw the production of national-level topic or response chapters and were in charge administratively of their chapter's development.

Federal Coordinating Lead Authors (CLAs) were selected for each chapter—some chapters had two—by the NCA4 SC, in consultation with the SGCR. A key role of the CLAs was to serve as "horizontal integrators" for NCA4—working with one another to ensure that crosscutting issues were addressed consistently, accurately, and adequately. They also ensured that the chapter draft ultimately delivered to them adhered to their Agency's criteria for a Highly Influential Scientific Assessment.

Chapter Leads (CLs; both federal and non-federal) served as "vertical integrators" for NCA4, selecting and directing their respective author team and then providing a draft of their chapter to the CLA(s). National Chapter Leads (NCLs), for the topic and response chapters, were selected by the ACL for the chapter, while the Regional Chapter Leads (RCLs) were selected from experts nominated during a public open call by the NCA4 SC.

Chapter Authors (CAs) constituted the bulk of the chapter author team and were the main authors of the individual chapters. The CLs directed the CAs to contribute to the writing and editing of the chapters. The CLs chose the CAs based on the specific needs of the chapter. CLs were provided guidance to convene a diverse group of experts along with the full slate of nominees received during the public call for authors.

Review Editors (REs) were selected by the NCA4 SC after a public call for nominees. They were responsible for ensuring that all substantive comments—submitted during the Public Comment Period and via a National Academies of Sciences, Engineering, and Medicine (NASEM) expert review panel—were appropriately addressed and documented. REs advised CLs on how to handle contentious issues and to ensure that significant scientific uncertainties were reflected adequately in the text of NCA4.

Technical Contributors (TCs) were invited to contribute to the chapter author team for discrete, specific issues on an as-needed basis, as identified by the CL.

The USGCRP **National Coordination Office (NCO)** in Washington, DC, provided support for the development of NCA4 through a team of contracted staff and federal detailees with expertise in planning, writing, and coordinating collaborative climate and environmental science activities. NCO staff provided monthly updates on NCA4 progress and activities to the SGCR Principals, while also—beginning in February 2017—posting similar content at http://www.globalchange.gov/news so the public could track progress.

The **NCA Technical Support Unit (TSU)** is funded by NOAA and is located at NOAA's National Centers for Environmental Information in Asheville, North Carolina; its professional staff supports the Assessment's climate science findings, data management and web design, graphics and publications, editing, and other production activities.

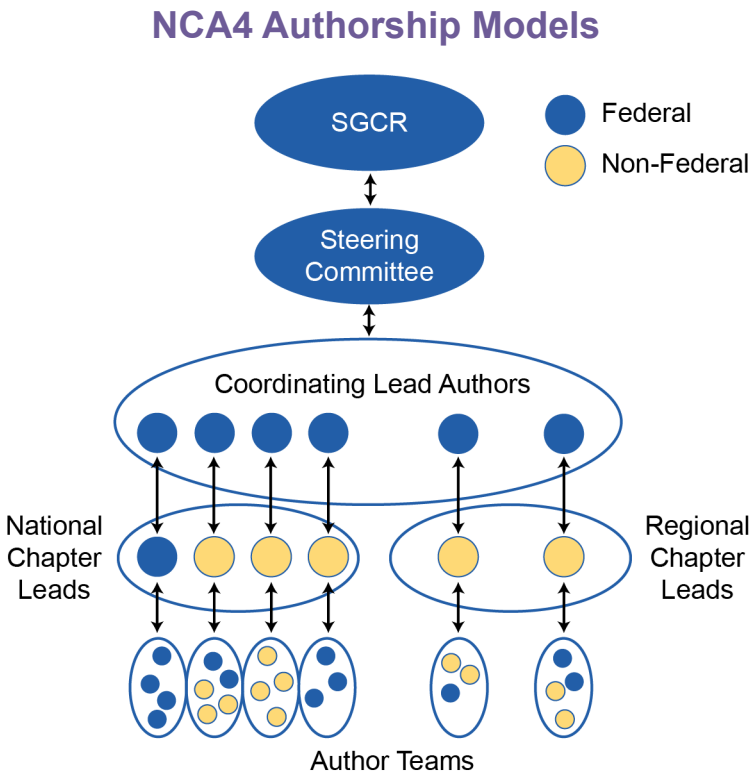

Figure A1.2: In consultation with the Subcommittee on Global Change Research (SGCR), the NCA4 Federal Steering Committee (NCA4 SC) selected Coordinating Lead Authors (CLAs) for each chapter of the NCA. CLAs worked one-on-one with either National or Regional Chapter Leads (CLs), who in turn directed Chapter Authors (CAs). A mix of authorship models including both federal and nonfederal participants was used for NCA4. Source: USGCRP.

Organization of the National Climate Assessment Participants

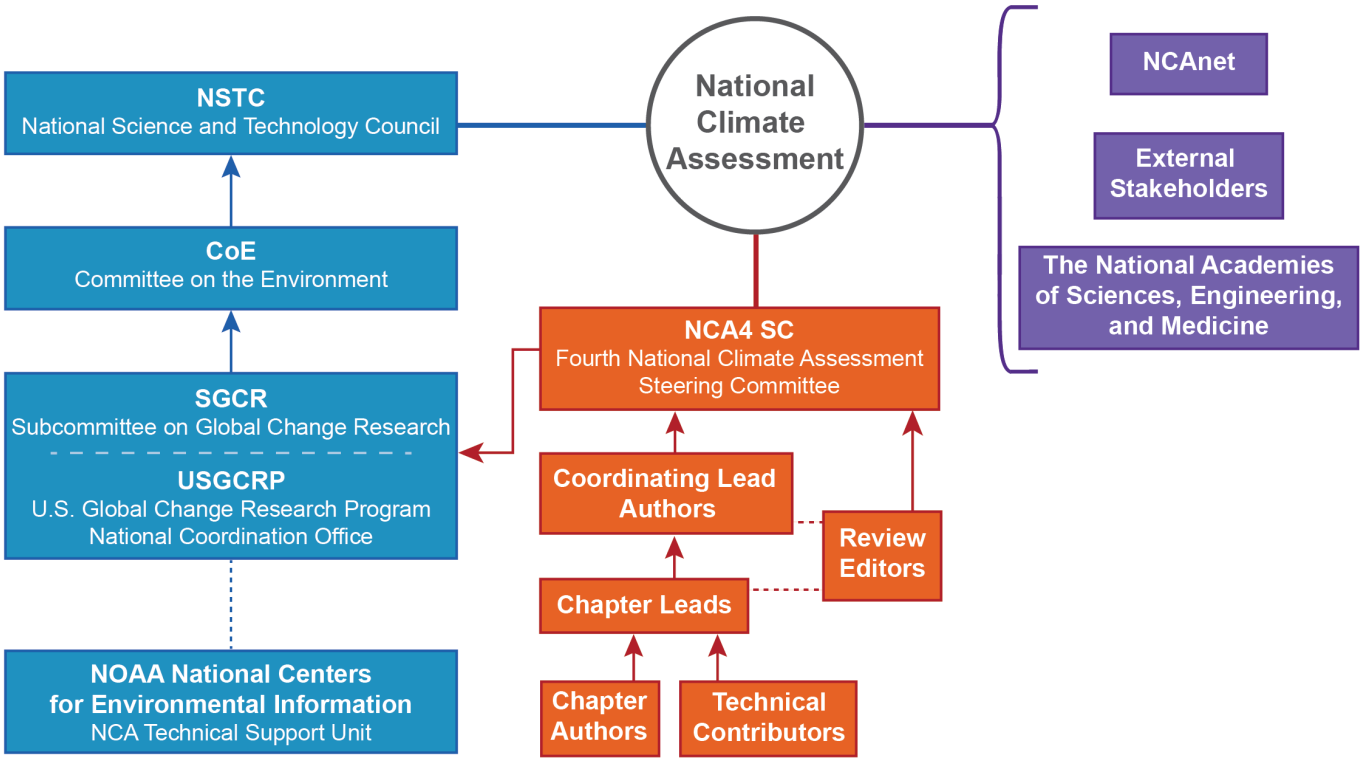

Figure A1.3: Participants in the NCA process can be divided into three broad categories: 1) federal agencies and offices, including the USGCRP (blue boxes); 2) external partners and relevant stakeholders (purple boxes); and 3) NCA4 contributors, including the Federal Steering Committee and report authors (orange boxes). Source: USGCRP.

The **National Climate Assessment Network (NCAnet)** consists of more than 200 organizations that work with the NCO, report authors, and USGCRP agencies to engage producers and users of assessment information.[7] Partners extend and amplify the NCA process and products to a broad audience through the development of assessment-related capacities and products, such as collecting and synthesizing data or other technical and scientific information relevant to the NCA, disseminating NCA report findings to a wide range of users, engaging producers and users of assessment information, supporting NCA events, and producing communications materials related to the NCA and NCA report findings.

Creating the Fourth NCA Report

Process Development

In May 2015, a Federal Register Notice[8] requested information to help inform the structure and content of USGCRP's sustained National Climate Assessment process, which NCA4 is a part of. In early 2016, the SGCR Principals designated the NCA4 SC to lead NCA4 development, and the NCA4 SC began its work, building on prior work from the Interagency National Climate Assessment (INCA) Working Group, the NCADAC, experiences of TSU and NCO staff, and feedback from the aforementioned public call for information (Figure A1.4).

In July 2016, a Federal Register Notice[9] was published, seeking input on the draft outline for NCA4. Subsequently, a Federal Register Notice[10] was published in late August 2016,

serving as both a call for regional Chapter Leads and other authors (open call for 30 days) and a call for technical inputs (this part of the call was open for a longer time period, until mid-January 2017).

Concurrent with these public calls for nominations and technical inputs, the NCA4 SC, NCO staff, and TSU staff developed guidance documents for use during the development of NCA4, ranging from chapter and Traceable Accounts templates to style guides and a literature resource database. Risk-based framing was integrated into the chapter templates and other drafting guidance. Authors had access throughout the process to scientific resources and writing guidance materials on a password-protected Resources website, hosted by the TSU, that also served as a collaboration space for authors.

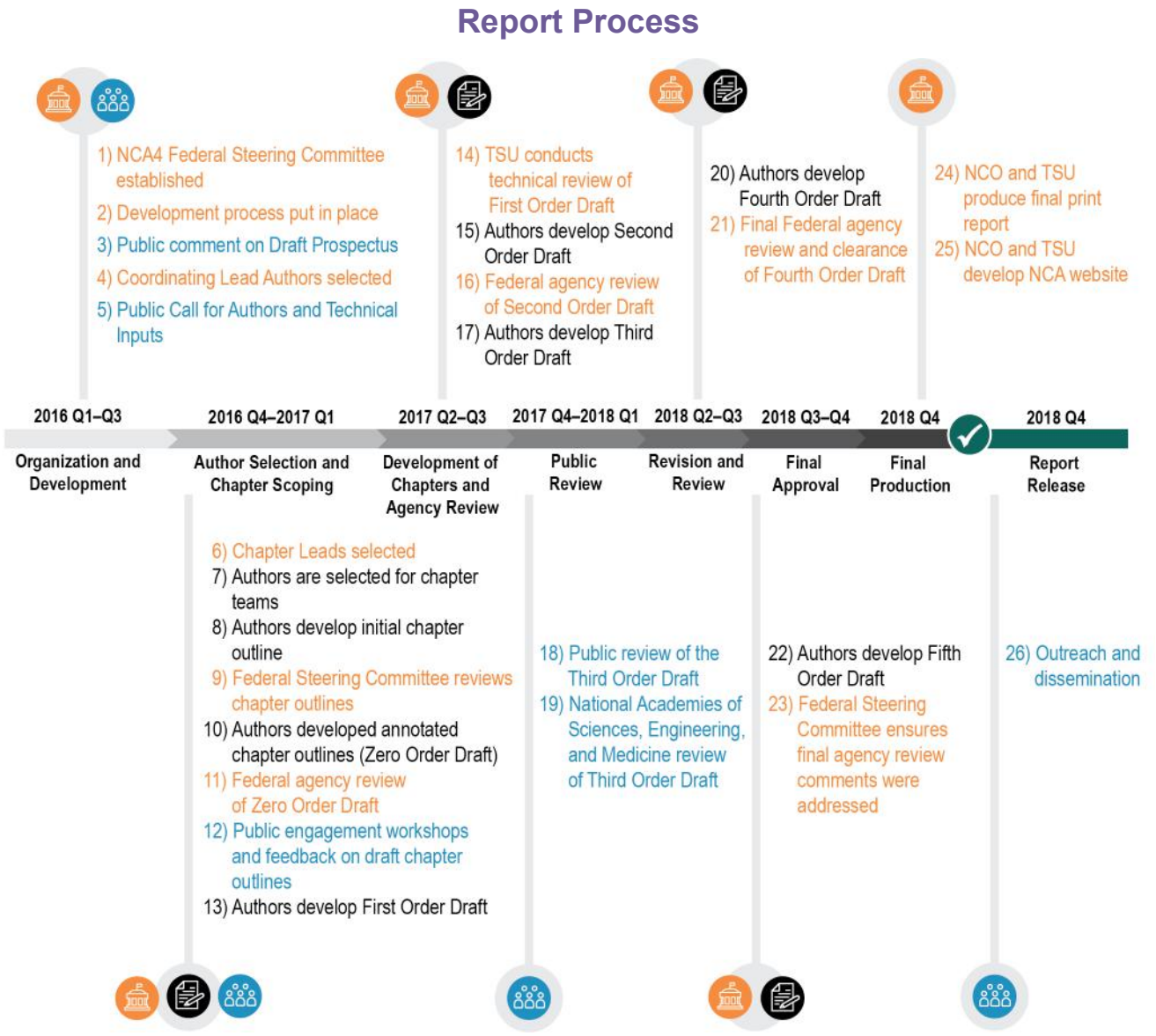

Figure A1.4: This is a graphic illustration of the NCA4 development process. Multiple points of federal review and decision (orange icons) were present throughout the process. In addition, public engagement (blue icons) was a cornerstone of the NCA development process. Authors used these feedback mechanisms to inform the development and execution of their chapters (black icons). Source: USGCRP.

Author Selection, Role, and Preliminary Work (Autumn 2016)

In the fall of 2016, the NCA4 SC selected one or two federal **Coordinating Lead Authors** (CLAs) for each chapter, based on criteria that included expertise and experience and that ensured a variety of perspectives. As the author teams were being assembled (described below), the CLAs and many of the CLs began scoping their chapters. In addition, in October 2016, a CLA meeting was held in Washington, DC, to provide context and guidance for the CLAs moving forward with the NCA4 process.

National Chapter Leads (NCLs), for the topic and response chapters, were selected by the Agency Chapter Lead for each national chapter. The NCA4 SC selected the **Regional Chapter Leads** (RCLs) from a pool of nominated authors derived from a call for nominations in the Federal Register Notice,[10] described above. These NCLs and RCLs, with input and guidance from the NCA4 SC, selected federal and nonfederal **Chapter Authors** (CAs) to establish chapter author teams. CAs were identified based not only on the expertise and experience they would bring to the chapter, but also a commitment to ensuring that a diverse range of perspectives would be reflected in the drafting process. In addition, **Technical Contributors** (TCs) were enlisted at the discretion of the CL to provide specific technical input to the chapter as needed. Each chapter had a primary and backup NCO **Point of Contact** (POC) who supported the chapter team, provided clarity on drafting guidance, facilitated conversations, and assisted the CLA in identifying crosscutting issues.

Initial Chapter Outlines (December 2016 – January 2017)

Authors developed initial chapter outlines in December 2016. The NCA4 SC provided comments on these, which resulted in more complete chapter outlines in January 2017. An interagency review led by the SGCR provided a higher-level review of these more detailed outlines to further inform the development of each chapter.

Regional Engagement Workshops, Author Meetings, and Other Chapter Engagement (Spring 2017)

During late winter and early spring 2017, a series of **Regional Engagement Workshops** (REW; Figure A1.5) and National Chapter Engagement Webinars provided stakeholders with the opportunity to learn about the NCA4 process and provide additional input to author teams as they worked to deliver a First Order Draft of their chapters in June 2017. The hub-and-satellite model (a central hub with various additional sites around the region joining virtually) employed for the REWs resulted in participation in 44 cities and towns across the United States, reaching thousands of stakeholders. Workshop summary reports were shared with all NCA4 author teams to provide a consistent foundation for all report authors. These summary reports are available online at http://www.globalchange.gov/content/nca4-engagement-activities.

In addition, NCA4 authors, staff, and NCAnet affiliates organized, spoke at, and participated in a number of sessions at professional society meetings, web-based seminars, community meetings, and other events designed to provide a two-way exchange of information between NCA users and contributors.

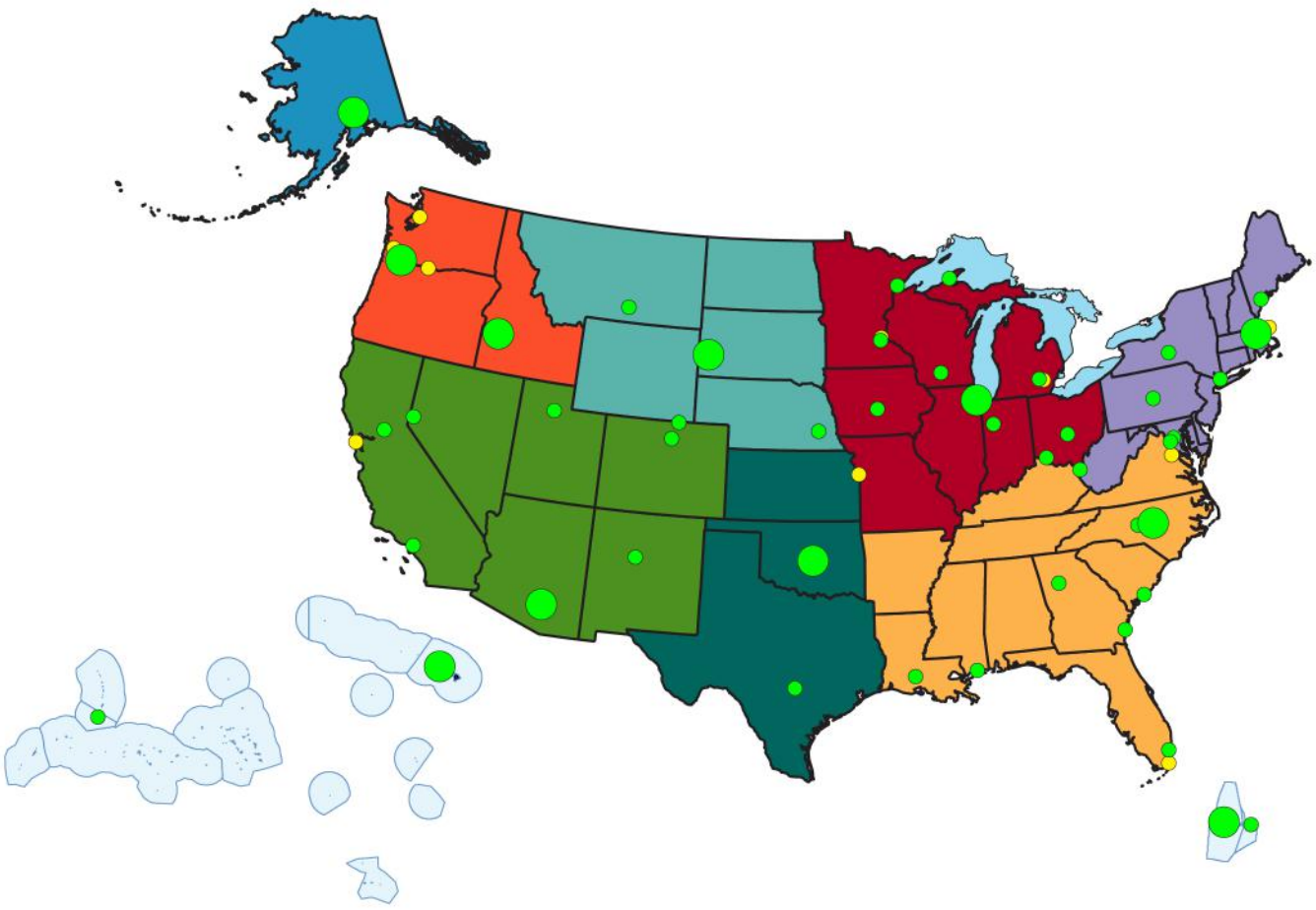

Figure A1.5: The large green dots illustrate the hub locations for the 11 Regional Engagement Workshops held across the country in February to March of 2017. The small green dots indicate satellite locations for those workshops, and the small yellow dots show the locations of some additional engagement activities, such as presentations or listening sessions at professional society meetings. Source: USGCRP.

Regional Engagement Workshops

Figure A1.6: Regional engagement workshops were held around the country in every NCA4 region to facilitate feedback from interested stakeholders on the outlines of the regional chapters. Workshops in San Juan, Puerto Rico, Norman, Oklahoma, Portland, Oregon, and Rapid City, South Dakota, are highlighted. Photo credits: (San Juan, PR photos) Gary Potts, USFS; (all others) USGCRP.

First Chapter Leadership Meeting (CLA-CL1)

On April 4–5, 2017, chapter leadership (CLAs and CLs) convened in Washington, DC, to work on cross-chapter coordination and to discuss additional guidance on chapter drafting, especially on Key Message and Traceable Account formulation. A particularly successful component of this two-day meeting was an extended "speed-dating" session, where CLAs and CLs from a given chapter would meet with their counterparts from another chapter for 30 minutes to discuss how crosscutting issues would be addressed in their respective chapters to ensure consistent, nonduplicative coverage of key issues.

First Chapter Leadership Meeting

Figure A1.7: Chapter leadership gathered in Washington, DC, for a two-day meeting intended to facilitate individual National Climate Assessment chapter development, inform leadership on process and logistical needs, and facilitate cross-chapter collaboration and information sharing. Photo credits: USGCRP.

Author Training and Drafting

Each of the author teams met multiple times by phone, web, and in person and produced multiple iterations of their chapters since beginning work in October 2016. Traceable Accounts developed for the chapters provide transparent information about the authors' deliberations to arrive at their expert judgment regarding the level of certainty related to the Key Messages of their chapter.

Monthly calls/webinars were generally held with all authors in order to provide them with updates and to address a variety of topics in an effort to ensure consistency across the report and to keep the Assessment progressing in a timely manner. In addition, USGCRP coordinated 14 author training webinars on the following topics:

- Available scenarios products and how to use them
- The EPA's Climate Change Impacts and Risk Analysis (CIRA) project[11]
- Lessons learned through previous assessments
- Key Message and Traceable Account development
- A walkthrough of the website for scenario products[12]
- Available regional- and local-scale climate variables, through the Localized Constructed Analogs (LOCA) system (see App. 3: Data & Scenarios for more information)
- Metadata requirements and the Global Change Information System (GCIS)
- Climate change indicators
- A report from the National Academies of Sciences, Engineering, and Medicine (NASEM) on *Characterizing Risk in Climate Assessments*[13]
- Risk-based framing
- *Climate Change and Indigenous Peoples: A Synthesis of Current Impacts and Experiences* report[14]
- NCA4 Volume I: *Climate Science Special Report* (CSSR)
- NOAA's State Climate Summaries[16]
- External, expert peer-review of the draft report by an ad hoc panel of NASEM[17]

All author training webinars were recorded and archived on the password-protected Resources portal for authors to access at their convenience throughout the process.

Cross-Chapter Coordination

A key component of success in any broad assessment effort is a means of facilitating cross-chapter coordination. During NCA4, this was done throughout the drafting and review processes. The CLA-CL1 meeting facilitated high-level information sharing among chapter leadership, especially through the aforementioned speed-dating meetings between chapters. The Resources website also provided a forum for interim drafts to be posted and viewed by all author teams.

Specific author teams employed many other techniques. For example, the regional authors working on tribal and Indigenous topics began having regular phone meetings in the winter of 2017 and then began meeting with the authors of the national-level "Tribes and Indigenous Peoples" chapter to discuss consistent terminology and language framing around these topics. Authors of another national-scale

chapter (Ch. 10: Ag & Rural) set up phone calls with authors from each of the regional chapters to ensure appropriate coverage of topical issues throughout the regions and to facilitate the roll-up of regional issues related to agriculture and rural communities to the higher-level synthesis chapter.

Review Editor Selection and Role

The NCA4 Federal Steering Committee selected Review Editors (REs) from a slate of candidates nominated through a public open call in the summer of 2017.[18] For their assigned chapter(s), REs ensured that all substantive comments submitted during the Public Comment Period and via an expert review panel of NASEM were appropriately addressed and documented. REs advised CLs on how to handle contentious issues and ensured that significant scientific uncertainties were reflected adequately in the text of NCA4. REs did not provide additional comments on assigned draft chapters but instead focused on the materials derived from the Public Comment Period and NASEM review. REs ensured that each and every comment had been considered by the author team and that the "annotation" (the written response to the comment) was responsive to the comment and indicated any revision made to the chapter(s), including the scientific or logical rationale for said action. REs helped the CLs ensure that the response to each review comment matched the final text of the revised, post-public/NASEM review draft.

All-Author Meeting

On March 26–28, 2018, all chapter authors and review editors were invited to participate in a 2.5-day all-author workshop in Bethesda, Maryland. The workshop gave authors the opportunity to finalize cross-chapter references and finish edits in response to both public and NASEM reviews of the Third Order Draft.

Review Processes

To begin the writing process, author teams were instructed to develop high-level chapter outlines late in 2016 in light of comments received on the draft prospectus[9] and guidance provided to authors. The NCA4 Federal Steering Committee reviewed and provided comments on these high-level chapter outlines, which resulted in annotated outlines (Zero Order Drafts) provided to the SGCR for interagency review in January 2017. Comments from this interagency review, alongside input from the suite of public engagement events held throughout the spring of 2017, informed the development of a full First Order Draft.

With the receipt of the full First Order Draft in mid-June 2017, the TSU began an iterative technical editing process with the authors of each chapter to ensure that content was scientifically accurate, that topics were addressed consistently across chapters, and that the text and figures were accessible to the target audience. This process resulted in a Second Order Draft (SOD). A second round of interagency, SGCR-led review of this SOD occurred in the summer of 2017. Consequently, authors revised their chapters in response to these interagency comments, resulting in a Third Order Draft (TOD). This TOD was then released on November 3, 2017, for review by the public.[19] The three-month public review period allowed individuals and groups to examine the draft and provide comments to ensure that the report 1) presented the science accurately, 2) responded to user needs, and 3) relayed its findings in a clear and consistent manner. By the time the Public Comment Period closed on January 31, 2018, the online comment system had received 3,416 comments representing diverse perspectives from over 1,100 registrants (although a smaller number of individual registrants actually submitted comments). Concurrent to this public review period, NASEM convened an expert ad hoc committee to review the TOD and provided the authors with a formal, peer-reviewed external expert review.[17]

All-Author Meeting

Figure A1.8: Author teams gathered in Bethesda, Maryland, in March 2018 to finalize revisions in response to public and NASEM reviews (c, f) and to collaborate across chapters to ensure coherency across the report (a, d, e). More than 200 authors attended the meeting (b). Photo credits: USGCRP.

Chapter author teams amended the TOD in response to these public and NASEM comments; they were required to respond to each and every comment. Review Editors evaluated the adequacy of the responses to the comments on each chapter. The public comments and the chapter authors' responses to those comments are available online with the final report (https://nca2018.globalchange.gov/downloads/).

The Fourth Order Draft (4OD) that resulted from the revisions made in response to the public and NASEM comments was then circulated to the interagency again for final federal review and clearance in late April 2018. Any comments that were submitted by the early June 2018 deadline were addressed by the authors during the summer of 2018, resulting in a Fifth Order Draft. In late summer 2018, each Agency's Federal Steering Committee member reviewed this final draft of the report to ensure that any agency comments submitted by the June deadline were adequately addressed.

NCA Final Report

After a production and layout phase in the autumn of 2018, a final public version of the report was published as a downloadable PDF in December 2018; an accompanying website (nca2018.globalchange.gov) was unveiled at the same time. A number of derivative products, including a "Report-in-Brief" document, were produced in addition to the full report.

Resources Available for Authors

The **Resources website** served as the primary compendium of guidance documents, recordings of training webinars, drafts in progress, and many other resources for authors. In addition, the Resources site contained forms to submit figure requests and the associated, required metadata.

Technical Inputs

A public call for technical inputs[10] resulted in the submission of more than 400 peer-reviewed journal articles, reports, and other contributions authored by hundreds of individuals from academia, industry, various levels of government, and nongovernmental organizations. Alongside this public set of technical inputs, the USGCRP NCO conducted a survey of high-impact scientific journals and other peer-reviewed sources to develop a searchable-by-chapter database of over 1,200 articles and reports for NCA4 authors to consider in their assessment.

In addition, the TSU climate science team developed 51 state climate summaries (one for each state, with a 51st summary on Puerto Rico and the U.S. Virgin Islands) to meet a demand for state-level information in the wake of NCA3.[16] The summaries cover assessment topics directly related to NOAA's mission, specifically historical climate variations and trends, future climate model projections of climate conditions during the 21st century, and past and future conditions of sea level and coastal flooding. Furthermore, EPA produced 50 state climate summaries plus one each for Guam, Puerto Rico, and the U.S. Virgin Islands, looking at historical climate impacts.[20]

The *Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment* (CIRA2.0) was produced as a technical input to NCA4 and informs many chapters.[11] This report estimates the physical and monetary benefits to the United States of reducing global greenhouse gas emissions in 2050 and 2090 for more than 20 sectors of the American economy. Other technical reports produced since NCA3 and used as technical inputs to NCA4 include the U.S. Forest Service's *Effects of Drought on Forests and Rangelands in the United States: A Comprehensive Science Synthesis*[21] and *Climate Change and Indigenous Peoples: A Synthesis of Current Impacts and Experiences*.[14]

Special Assessment Reports

A number of federally produced scientific assessment reports provide a robust foundation from which NCA4 authors drew. An illustrative list of such USGCRP-sustained assessment products include:

The *Climate Science Special Report* (CSSR),[15] released in November 2017, is Volume I of NCA4. It provides the scientific underpinnings for NCA4 and serves as an update of the physical science as presented in NCA3.[2] Topics include detection and attribution; precipitation change; droughts, floods, and wildfire; extreme storms; sea level rise; ocean acidification; mitigation; potential surprises; and more.

The *Second State of the Carbon Cycle* (SOCCR2)[22] was released in December 2018 and provides an update on carbon cycle science across North America that informs several NCA4 chapters.

The *Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* (referred to as the "Climate and Health Assessment") was released in April 2016 and strengthens our understanding of the linkages between climate change and health. It serves as an important input to NCA4,[23] covering such issues as temperature-related death and illness; air quality impacts; extreme events; vector-borne diseases; waterborne illness; food safety, nutrition, and distribution; mental health and well-being; and populations of concern.

The *Climate Change, Global Food Security, and the U.S. Food System* assessment was released in December 2015 and identifies climate change impacts on global food security. It provides input to many chapters,[24] covering such issues as non-climate drivers of food systems and security; models, scenarios, and projections of socioeconomic change; integrated assessment models of agricultural and food systems; food availability and stability; food access and stability; food utilization and stability; and global food security and the United States.

The *Third National Climate Assessment* (NCA3) was released in 2014 and covered many of the same sectors and geographical regions of the United States, providing a foundation for the sectors and regions in NCA4.[2] NCA4 includes several new national topic chapters and regions as a result of feedback from the public for such information.

Engagement Activities

The NCA Engagement Strategy,[25] developed for NCA3 and expanded for NCA4, provides a vision for participation, outreach, communications, and education processes that help make the NCA process and products more accessible and useful to many audiences. The overall goal of engagement is to create a more effective and successful NCA that is informed by and responsive to user needs—improving the processes and products of the effort so that they are credible and salient and build the capacity of participants to engage in the creation and use of these processes and products for decision-making.[25] The strategy describes a number of mechanisms through which scientific and technical experts, decision-makers, and members of the general public might learn about and participate in the NCA process.

The NCO organized listening sessions, symposia, webinars, and other sessions at professional society meetings to provide updates on the NCA process, solicit broad input from subject matter experts, and collect feedback on the approach, topics, and methodologies under consideration.

A series of **Regional Informational Webinars** were conducted in September 2016 to solicit technical inputs and nominations for authors and to discuss the NCA4 process. These included webinars targeted at each of the NCA4 regions (with the Southeast and U.S. Caribbean being combined), as well as one webinar focused on tribal and Indigenous communities and a final, national-level webinar intended for a general audience.

In addition, a series of **Public Comment Period Webinars** were offered from November 2017 through January 2018 to raise awareness of the opportunity for the public to review the Third Order Draft of NCA4.

NCO staff also provided substantive updates on process and development directly to NCA authors in **weekly emails** and **monthly calls**. The broader public was kept abreast of developments through **regular updates** on the USGCRP website: http://www.global-change.gov/nca4.

NCAnet Activities

USGCRP hosts an NCAnet (NCA network) Conversation on a roughly bimonthly basis (since January 2012). Briefly, NCAnet is a network of organizations working with the NCA to engage producers and users of assessment information across the United States. Participants (http://ncanet.usgcrp.gov/partners) help extend the reach of USGCRP assessment products, including the NCA and reports like the Climate and Health Assessment (https://health2016.globalchange.gov/), through the development of assessment-related capacities and products. These efforts have included collecting and synthesizing data or other technical and scientific information relevant to current and future assessments, disseminating findings to various users of assessment information, engaging assessment information producers and users, supporting assessment-related events, and producing communications materials related to the NCA and other assessment findings.

More information on NCAnet, including a list of NCAnet affiliates and presentations, as well as information on becoming a member, is available at http://ncanet.usgcrp.gov.

Regional Engagement Workshops and Subsequent Author Meetings

In order to gain feedback from the residents of the various NCA4 regions, author teams held workshops in various locations and invited members of the public and interested stakeholders to listen to presentations on the proposed chapter outlines. Attendees were then asked to provide feedback to authors to help clarify the priorities of the region, relay valuable technical inputs, and otherwise inform the development of the chapter. Reports from these workshops are available online at https://www.globalchange.gov/content/nca4-engagement-activities.

- Alaska Regional Engagement Workshop, Hub: Anchorage, Alaska, February 2017
- Northeast Regional Engagement Workshop, Hub: Boston, Massachusetts, with six satellite locations, February 2017
- Southwest Regional Engagement Workshop, Hub: Tucson, Arizona, with six satellite locations, February 2017
- Northern Great Plains Regional Engagement Workshop, Hub: Rapid City, South Dakota, with three satellite locations, February 2017
- Hawai‘i and U.S.-Affiliated Pacific Islands Regional Engagement Workshop, Hub: Honolulu, Hawai‘i, March 2017
- Midwest Regional Engagement Workshop, Hub: Chicago, Illinois, with nine satellite locations, March 2017
- Southern Great Plains Regional Engagement Workshop, Hub: Norman, Oklahoma, with one satellite location, March 2017

- U.S. Caribbean Regional Engagement Workshop, Hub: San Juan, Puerto Rico, with one satellite location, March 2017
- Southeast Regional Engagement Workshop, Hub: Raleigh, North Carolina, with seven satellite locations, March 2017
- Northwest Regional Engagement Workshop, Hubs: Portland, Oregon, and Boise, Idaho, March 2017

Listening Sessions

Listening sessions were held in a number of places where a full workshop was not appropriate or possible. Listening sessions included a brief overview presentation on the NCA, with some specifics on the chapters of interest to the given audience. Stakeholders were then encouraged to provide feedback on the content of the presentation, as well as any additional information or resources that might be useful for authors to understand.

- Great Lakes Adaptation Forum, October 2016, Ann Arbor, Michigan
- The Kresge Foundation, November 2016, Washington, DC
- American Geophysical Union Annual Meeting, December 2016, San Francisco, California
- American Meteorological Society Annual Meeting, January 2017, Seattle, Washington
- Transportation Research Board Aviation Climate Change Subcommittee, January 2017, Washington, DC
- National Council for Science and the Environment National Meeting, January 2017, Crystal City, Virginia
- Alaska Center for Climate Assessment and Policy Webinar, February 2017
- Association for the Sciences of Limnology and Oceanography, March 2017, Honolulu, Hawai'i
- National Adaptation Forum, May 2017, St. Paul, Minnesota

Presentations

Many presentations were given to relevant stakeholder audiences through the development of this report. An illustrative listing of NCA4-related presentations made by NCO staff includes:

- North American Carbon Program Science Leadership Group–NCA4 Overview, October 2016, Crystal City, Virginia
- Resilience AmeriCorps Federal Resource Fair, October 2016, Alexandria, Virginia
- 2016 Belmont Forum Plenary Meeting, November 2016, Doha, Qatar
- 7th Annual Northwest Climate Conference, November 2016, Stevenson, Washington
- American Lung Association, December 2016, Washington, DC
- American Geophysical Union Annual Meeting (NASA and NOAA booths), December 2016, San Francisco, California
- Transportation Research Board–Climate Change and Energy Task Force, January 2017, Washington, DC
- American Meteorological Society Annual Meeting Booth, January 2017, Seattle, Washington

- National Council for Science and the Environment Annual Meeting, January 2017, Crystal City, Virginia
- American Association for the Advancement of Science Annual Meeting, February 2017, Boston, Massachusetts
- 2017 Joint NACP Ameriflux Principal Investigators Meeting, March 2017, North Bethesda, Maryland
- Southeast & Caribbean Climate Community of Practice 2017 Meeting, April 2017, Charleston, South Carolina
- Association of State Floodplain Managers Annual Conference, May 2017, Kansas City, Missouri
- National Adaptation Forum, May 2017, St. Paul, Minnesota
- Conference of Mayors Annual Meeting, June 2017, Miami Beach, Florida
- Ecological Society of America Annual Meeting, August 2017, Austin, Texas
- American Chemical Society National Meeting, August 2017, Washington, DC
- Pacific Northwest Climate Conference, October 2017, Tacoma, Washington
- Geological Society of America Annual Meeting, October 2017, Seattle, Washington
- Guest lecture at Boston University, November 2017 (virtual)
- American Geophysical Union Fall Meeting, December 2017, New Orleans, Louisiana
- American Meteorological Society Annual Meeting, January 2018, Austin, Texas
- National Council for Science and the Environment Annual Meeting, January 2018, Crystal City, Virginia
- Guest lecture at San Francisco State University, February 2018 (virtual)
- National Association of Regulatory Utility Commissioners Winter Policy Summit, February 2018, Washington, DC
- Air and Waste Management Association webinar, February 2018 (virtual)
- American Association for the Advancement of Science Annual Meeting, February 2018, Austin, Texas
- Center for Climate and Energy Solutions Business Environmental Leadership Council Spring Meeting, March 2018, Washington, DC
- Guest lecture at University of Illinois, April 2018 (virtual)
- Guest lecture at University of Arizona, April 2018 (virtual)
- Electric Power Research Institute (EPRI) Energy 7 Climate Research Seminar, May 2018, Washington, DC
- Adaptation Futures Conference, June 2018, Cape Town, South Africa
- American Association of State Climatologists Annual Meeting, June 2018, Nebraska City, Nebraska

- National Academies of Sciences, Engineering, and Medicine Committee to Advise USGCRP, July 2018, Washington, DC
- Ecological Society of America Annual Meeting, August 2018, New Orleans, Louisiana
- National Academies of Sciences, Engineering, and Medicine Workshop on Subnational Climate Assessments, August 2018, Washington, DC
- Great Lakes Adaptation Forum, September 2018, Ann Arbor, Michigan
- Sigma Xi Annual Meeting, October 2018, Burlingame, California
- American Geophysical Union Fall Meeting, December 2018, Washington, DC

Sustained Assessment: Past, Present, and Future

The concept of, motivation for, and ideas to inform a sustained assessment process were articulated in Chapter 30 of NCA3, "Sustained Assessment: A New Vision for Future U.S. Assessments,"[26] and the NCADAC Special Report, "Preparing the Nation for Change: Building a Sustained National Climate Assessment Process."[27] In addition, the Interagency National Climate Assessment (INCA) Working Group provided thought leadership and implementation options in response to recommendations laid out in the above reports.

NCA4 was developed within a sustained assessment framework and process, drawing on these previous efforts, as well as an evaluation of the NCA3 process.[6] As part of this sustained assessment process, NCA4 built on and utilized products, indicators, and tools developed since NCA3 (many of which are described in detail in App. 3: Data & Scenarios). In addition, in response to gaps identified in NCA3, NCA4 is placed in a broader international context (detailed in the new chapter "Climate Effects on U.S. International Interests" and in the new appendix "Looking Abroad: How Other Nations Approach a National Climate Assessment"). The Climate Change Impacts and Risk Analysis (CIRA) project responds to a recommendation for additional work on quantifying the economic impacts of climate change across sectors of the American economy.[11] The CIRA report's project leaders not only provided information tailored to each NCA4 region and most sectors but also worked with many individual chapters through webinars, conference calls, and other collaborative interactions. Guidance on uncertainty and confidence treatment was also provided early on to NCA4 authors, responding to another sustained assessment recommendation.

While the aforementioned efforts provided a useful foundation on which NCA4 could be informed through a sustained assessment lens, greater efficiency and efficacy can be realized under a sustained assessment framework. In an effort to make that a reality, two groups were constituted to further elucidate what such a process could look like.

The **Advisory Committee for the Sustained National Climate Assessment (ACSNCA)** was a 15-member federal advisory committee established by the Department of Commerce on behalf of the USGCRP to advise SGCR on the sustained assessment process and stakeholder engagement. Its primary focus was not on NCA4 but on future assessment processes and engagement work around the NCAs. The ACSNCA met in person biannually and more frequently on teleconferences, with its first in-person meeting being held in September 2016. The original two-year charter for the ACSNCA expired in 2017 and was not renewed.

The **Sustained Assessment Interagency Working Group (SAWG)** provides an interagency forum for agencies to deliberate upon ideas for the various components composing a sustained assessment process. The SAWG holds monthly meetings attended by a diverse array of interagency experts, including SGCR Principals, USGCRP Interagency Working Group co-chairs and members, NCA4 Federal Steering Committee members, representatives from regional science organizations (for example, NOAA Regional Integrated Sciences and Assessments offices, DOI Climate Adaptation Science Centers, USDA Climate Hubs, etc.), and staff at the NCA4 Technical Support Unit. The SAWG first met in early 2017, when members began by reorienting themselves with the NCADAC recommendations and the options put forward by INCA. In ensuing months, thematic issues were discussed, bringing in outside experts to suggest ideas for next steps on a range of topics, including foundational elements, data tools and scenario products, special reports, user engagement, contributor engagement, harvesting assessments for research priorities, evaluation, and a vision and process for NCA5 and beyond.

The ultimate objective is to develop a process that includes activities inside and outside the Federal Government, makes efficient use of limited federal resources, and—importantly—is informed by and responsive to evolving user needs.

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A2 Appendix 2. Information in the Fourth National Climate Assessment

The Fourth National Climate Assessment (NCA4) synthesizes information about the impacts of climate change in the United States. As a *highly influential scientific assessment* (HISA), information cited within NCA4 must meet the standards of the Information Quality Act (IQA).

Identification of Literature Sources

This report assessed information from several sources, including 1) technical input reports and scientific resources collected for the Third National Climate Assessment;[1] 2) the *Climate Science Special Report*[2] and other U.S. Global Change Research Program (USGCRP) science assessments; 3) a literature database comprising over 1,000 original reports meeting IQA requirements, compiled by USGCRP staff and shared with authors; 4) a public request for information released by the U.S. Department of Commerce in 2016;[3] 5) expert awareness of the literature from authors; 6) information provided during Regional Engagement Workshops and other engagement events;[4] and 7) chapter-specific submissions of technical resources and relevant literature to author teams.

The vast majority of sources used in this report are from peer-reviewed scientific literature. A library of relevant and significant peer-reviewed scientific literature was developed through a survey of scientific journals and through submissions collected via a Federal Register Notice (FRN). The FRN, published by the U.S. Department of Commerce on behalf of USGCRP on August 31, 2016, called for the public to submit "recent, relevant scientific and/or technical research studies including observed, modeled and/or projected climate science information that have been peer-reviewed and published or accepted for publication in scientific journals and/or government reports."[3] In addition, the FRN called for submission of information outside the scientific peer-reviewed literature, such as reports produced by nonprofit communities, but it noted that all information used in the report would need to comply with the IQA.

In addition, USGCRP hosted Regional Engagement Workshops in each of the 10 NCA4 regions, and several author teams hosted chapter-specific webinars or events (see App. 1: Process for additional details).[4] Each of these events enabled the public to provide author teams with additional resources and information. As follow-up to these events, the public had access to chapter-specific email addresses to submit further resources to chapter author teams.[4]

Compliance with the Information Quality Act

During the chapter development process, author teams assessed the available literature (see individual chapter Traceable Accounts for additional details). Guidance on information quality was provided to the author teams to assist in this process, directing the author teams to rely primarily on peer-reviewed scientific literature.

In limited situations where information was available only outside peer-reviewed scientific literature or U.S. Government reports, author teams were provided with a decision tree to aid them in evaluating potential sources by addressing the following considerations:

- **Utility:** Is the particular source important to the topic of your chapter?
- **Transparency and traceability:** Is the source material identifiable and publicly available?
- **Objectivity:** Why and how was the source material created? Is it accurate and unbiased?
- **Information integrity and security:** Will the source material remain reasonably protected and intact over time?

As the administrative agency responsible for producing this report, the National Oceanic and Atmospheric Administration ensured that all referenced information adhered to its Information Quality Guidelines.[5]

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A3 Appendix 3. Data Tools and Scenario Products

Introduction

To enable National Climate Assessment (NCA) authors to do the in-depth analysis necessary to make the Fourth National Climate Assessment (NCA4) most useful, the U.S. Global Change Research Program (USGCRP) provided author teams with an array of data tools and scenario products. This appendix contains additional information on some of the materials available to NCA4 authors in developing their chapters. While designed in part with NCA4 authors in mind, this suite of "Tools for Informed Decision-Making" is intended to support the day-to-day work of resource managers, community planners, and scientists across the country.

Tools Within the Sustained Assessment Process

Since the completion of the Third National Climate Assessment (NCA3) in 2014,[1] a major focus of work among USGCRP and its affiliated agencies has been to establish a process to continually add to and improve the knowledge and resources available to decision-makers seeking to address climate risks. The motivation for and benefit from that process is to evolve the NCA from being a periodic snapshot of the state of climate science into a sustained effort that is not only responsive to changing conditions but also allows for the continuing incorporation of newly developed products and research. Beyond being useful for NCA4 authors, these tools also represent a mechanism for ongoing development and updating of materials. Such a continuous process could make assessment products more valuable for connecting research with decision-making, thus facilitating evaluation of the state of knowledge and establishing rigorous ways of documenting and responding to changes over time.

Scenario Products

Scenarios are coherent, internally consistent, and plausible descriptions of possible future states of the world. Scenarios may be quantitative, qualitative, or both. The components of a scenario are often linked by an overarching logic, such as a qualitative narrative of how the future may evolve.

Overview

The USGCRP is mandated to "assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change." To fulfill this mandate, the NCA evaluates risks that climate and global change pose to the United States. This entails addressing specific questions about what is at risk in a particular region or sector and how it might be affected in different potential futures. Scenarios that span a range of plausible future changes in key environmental parameters, such as weather and climate extremes, sea level, population, and land use, can help carry this out. USGCRP has therefore coordinated the development of a set of scenario products, accessible at https://scenarios.globalchange.gov/, to support NCA4 development. Specifically, NCA4 authors have been provided with a suite of high-resolution (downscaled) scenario products for the United States, covering (at least) the entire 21st century, to support chapter development.

Selection of Representative Concentration Pathways

NCA4 authors have grounded their assessment in an analysis of the widely used scenarios termed "Representative Concentration Pathways," or RCPs, that form the foundation for the majority of recent coordinated global climate model experiments. (RCPs are also discussed in this report's Front Matter.) Consistent with previous NCAs, NCA4 relies in part on climate scenarios and modeling efforts generated for the Intergovernmental Panel on Climate Change (IPCC) assessments. In May 2015, USGCRP released a memo outlining the decisions regarding climate-related scenarios and the rationale around them.[2] Specifically, USGCRP decided to use the RCPs[3,4] and associated model results from the Climate Model Intercomparison Project Phase 5 (CMIP5)[5] that underpinned the IPCC 5th Assessment Report (AR5), completed in 2013–2014.

The CMIP model results, as driven by the RCP scenarios, have similarly become standard reference inputs for virtually all work in the United States and internationally concerning climate change science, impacts, vulnerability, adaptation, and mitigation. It is, therefore, reasonable, practical, and in line with the expectations of the research community for NCA4 to use the most recently available model outputs from CMIP5, associated with the RCPs. CMIP5 climate data were widely available during the development of NCA4; products from the next phase of the CMIP project (CMIP6) were not available in time to support NCA4.

USGCRP further decided that NCA4 would focus primarily on RCP8.5 and RCP4.5 for framing purposes, while also considering other scenario information where appropriate (for example, RCP2.6). These RCPs capture a range of plausible atmospheric concentration futures that drive climate models. RCP8.5 is the high-end scenario (high emissions, high concentrations, large temperature increase) in the IPCC's AR5; it likewise serves as the high-end scenario for NCA4, similar to the use of IPCC's 4th Assessment Report (AR4) Special Report on Emissions Scenarios (SRES) A2 scenario in NCA3.[6] RCP4.5 is not the lowest scenario in AR5, but it is similar to the AR4 SRES low-end B1 scenario that was used in NCA3. RCP2.6 represents the low end of the range considered by AR5, but it also assumes significantly greater emissions reductions, even for current and near-term emissions, than previous low-end scenarios used by the IPCC. The range represented by RCP8.5 and RCP4.5, therefore, provides the most continuity and consistency with the IPCC scenarios used for framing purposes by the previous NCA3.

As simulated in CMIP5, all of the RCPs result in similar global temperature and sea level rise outcomes for the next few decades. However, by mid-century and beyond, differences between RCPs have a substantial effect on the climate and impact outcomes (see Ch. 2: Climate, Figure 2.2). The choice to focus on RCP8.5 and RCP4.5 for impacts, adaptation, and vulnerability analyses allows for an evaluation of near-term concerns for the Nation, as well as a robust and wide range of longer-term outcomes relative to the present.

Because RCPs intentionally focus on the outputs that are in turn fed into climate models (namely atmospheric concentrations), a wide range of future assumptions about underlying socioeconomic conditions, both at the global and national scale (for example, population growth, technological innovation, and carbon intensity of the energy mix), could plausibly be consistent with each of the RCPs used in NCA4. For this reason, further guidance on U.S. population and land-use assumptions was provided to authors, as discussed in the Products section of this chapter. Nevertheless, each RCP was developed by a separate modeling

team;[4] for illustration, some of the assumptions in those modeling runs include the following:

- The range of future global population projections within the RCPs falls within the range of the low and high United Nations population projections from 2003.

- The range of global gross domestic product (GDP) projections within the RCPs falls within the range of the 90th-percentile range of GDP scenarios found in the literature available prior to publication of the RCPs.

- RCP2.6, RCP4.5, and RCP6.0 represent intermediate scenarios from the literature, resulting in primary energy use of 750 to 900 EJ (exajoules) in 2100 or about double recent levels; RCP8.5 is a much more energy-intensive scenario.

- Because of assumptions about future viability of carbon capture and storage (CCS) technologies, *all* scenarios use greater amounts of coal and/or natural gas than in the year 2000.

- An important element of RCP2.6 is the use of bio-energy in combination with CCS, resulting in negative emissions by the end of century.

- All RCPs assume increasingly stringent air pollution control policies.

Comparing outcomes under RCP8.5 with those of RCP4.5 (and RCP2.6 in some cases) not only captures a range of uncertainties and plausible futures but also provides information about the potential benefits of mitigation. Comparing outcomes under the two pathways shows the degree to which significant emissions mitigation at the global scale can avoid some impacts and inform adaptation choices to the risks that are present even at the low-end scenario. The scenario range allows for an assessment of impacts at a variety of temperature thresholds.

Products

Overview

As noted earlier, NCA4 authors were provided with a suite of high-resolution (downscaled) scenario products for the United States, covering at least the entire 21st century, to assist them in the development of their chapters (hosted at https://scenarios.globalchange.gov). These included

- changes in the averages and extremes of key climate variables (for example, temperature and precipitation),

- relative sea level rise along the entire U.S. coastline,

- population change as a function of demographic shifts and migration, and

- changes in developed land use driven by these population changes.

Authors were encouraged to use the provided scenario products to help ensure consistency in underlying assumptions and to improve the ability to compare and synthesize across chapters. Authors used these scenario products to frame uncertainty in future climate as it related to the regional and sectoral risks that were the focus of their chapters—both uncertainty as a result of considering multiple RCPs and uncertainty due to limitations in our understanding of key climate system processes or our ability to fully represent these processes in earth system models.

To better assist the author teams in meeting their needs, and to reduce the potentially large volume of underlying scenario products from which the authors could potentially draw, NCA4 authors were encouraged to think of the

scenario products as being grouped into the following three USGCRP scenarios: "Lower," "Higher," and "Upper Bound" departures from current conditions (Table A3.1).

For example, given this assessment's emphasis on using a risk-based framework, authors were asked to consider low-probability, high-consequence climate futures. Addressing this potential future, in addition to more probable futures, is facilitated by considering the Upper Bound USGCRP scenario. These outcomes will often pose the greatest risks to society and thus must be considered in any comprehensive risk assessment.

Similarly, the authors were asked to consider how future trends in other critical, non-climatic stressors, including population growth and land-use change, may interact with climate change to exacerbate (or alleviate) climate-related risks. Authors have, therefore, been provided with scenarios of these additional drivers, grouped with the climate-related scenarios under the Lower, Higher, and Upper Bound USGCRP scenarios (see Ch. 17: Complex Systems for additional discussion on how non-climatic stressors can exacerbate climate-related risks).

Authors have used these scenario products to support a range of tasks within individual NCA4 chapters. Many chapters use scenario products for broad needs, such as general context-setting to illustrate a range of possible future outcomes in key drivers of risk and determinants of vulnerability. Others have applied them to bound the envelope of scientifically plausible future climate change in assessing regional or sectoral risks. Still others have used scenarios to place existing literature into the context of a consistent, coordinated set of possible future conditions in order to facilitate improved synthesis. All of these applications are valuable uses of these scenario products for both the NCA and its users.

USGCRP Scenarios

Scenario Inputs	Lower Scenario	Higher Scenario	Upper Bound Scenario
temperature means/extremes	RCP4.5 ensemble mean	RCP8.5 ensemble mean	95th percentile of RCP8.5
precipitation means/extremes	RCP4.5 ensemble mean	RCP8.5 ensemble mean	95th percentile of RCP8.5
sea level rise	"Intermediate-Low"	"Intermediate"	"Extreme"
population	"lower" (SSP2)	"higher" (SSP5)	"higher" (SSP5)
development land use	"lower" (SSP2)	"higher" (SSP5)	"higher" (SSP5)

Table A3.1: Scenario products are organized into three USGCRP scenarios based on their departure from current conditions. The Shared Socioeconomic Pathways (SSPs) are described in greater detail later in this chapter.

Downscaled Climate Information

Driven by stakeholder feedback and input seeking information about potential future climate change at much finer spatial scales than is typically generated by the state-of-the-art global climate models (which have horizontal resolutions on the order of 100 km, or about 62 miles), NCA4 authors were provided with CMIP5 model outputs that had been downscaled to finer scales using the LOcalized Constructed Analogs (LOCA) methodology.[7]

The LOCA method is a statistical technique to downscale climate model output to a smaller spatial scale, providing a much finer geographical resolution for analysis. In the LOCA method, the local simulated climate model field for each day is matched to examples in historical observations that resemble the climate model spatial distribution, called analog days. Since historical observations are sufficiently dense to represent local features, the resulting dataset provides a realistic representation of the local variability suitable for many impacts analyses.

Previous methods that utilized the same basic approach identified a set of days (typically 30) that resemble the climate model field over a large region and produced the downscaled field through an optimal weighting of the entire set of analog days.[8] The LOCA method improves on these earlier methods in several ways. First, the analog days are chosen separately for local regions, thus providing a more realistic choice of analog days at the local scale. Second, for most of the local region, the single analog day best matching the climate model simulation is used for downscaling, rather than averaging a set of days. This produces a better representation of extreme events.

The LOCA data include 32 CMIP5 models covering the 1950–2100 period, including the historical period of 1950–2005, as well as a higher scenario (RCP8.5) and a lower scenario (RCP4.5) for 2006–2100. The LOCA data include maximum temperature, minimum temperature, and precipitation at a daily resolution and at 1/16th-degree spatial resolution. The spatial coverage is the continental United States, southern Canada, and northern Mexico. LOCA data were not completely available for the U.S. Caribbean, Alaska, or Hawai'i and U.S.-Affiliated Pacific Islands regions for NCA4, but extending LOCA to include these locations is an area of active research.

Sea Level Rise Scenarios

The Federal Interagency Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Task Force, a joint task force of the National Ocean Council (NOC) and USGCRP, was charged with developing and disseminating future sea level rise and associated coastal flood hazard scenarios and tools for the entire United States to support coastal preparedness planning and risk management processes.

Two key subtasks of the overall Task Force effort were to 1) develop updated scenarios of global mean sea level (GMSL), and 2) regionalize these global scenarios for the entire U.S. coastline, to serve both as inputs into assessments of potential vulnerabilities and risks in the coastal environment and as key technical inputs into NCA4. In order to bound the set of GMSL rise scenarios for year 2100, the Task Force assessed the most up-to-date scientific literature on scientifically supported upper-end GMSL projections, including recent observational and modeling literature related to the potential for rapid ice melt in Greenland and Antarctica.

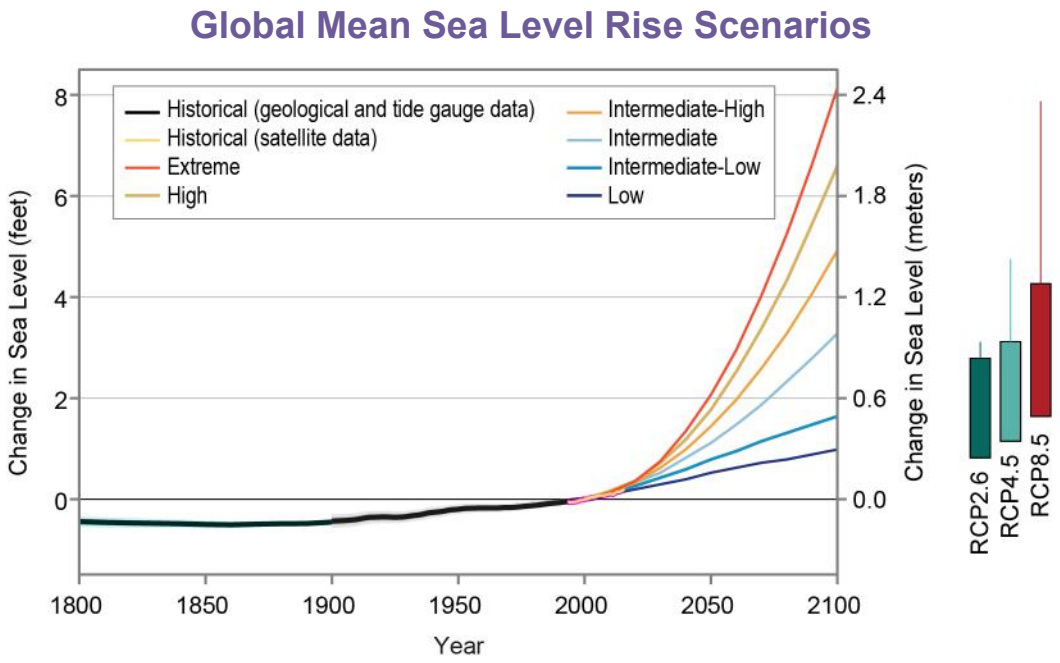

Figure A3.1: The figure shows observed (black and orange lines) and projected changes in global mean (average) sea level rise for 1800–2100. The projected changes are from six global average sea level scenarios developed for an interagency technical report.[9] The boxes on the right show the *very likely* ranges in sea level rise by 2100 (relative to 2000) corresponding to the three different RCP scenarios. The lines above the boxes show possible increases based on the newest research of the potential contribution to sea level rise from Antarctic ice melt. Source: Ch. 2: Climate, Figure 2.3, adapted from Sweet et al. 2017.[9]

This projected GMSL range was discretized into six GMSL rise scenarios at 0.5-meter increments (Low, Intermediate-Low, Intermediate, Intermediate-High, High, and Extreme, which correspond to a GMSL rise of 0.3 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m, respectively, by 2100). These were then used as the basis for deriving relative sea level (RSL) rise on a 1-degree grid covering the coastlines of the U.S. mainland, Alaska, Hawai'i, the U.S. Caribbean, and the U.S.-Affiliated Pacific Islands regions, as well as at the precise locations of available tide gauges along these coastlines. The RSL values account for key factors important at regional scales, including 1) shifts in oceanographic factors; 2) changes in Earth's gravitational field and rotation, and flexure of the crust and upper mantle due to melting of land-based ice; and 3) non-climatic factors mostly associated with vertical land movement (subsidence or uplift) due to glacial isostatic adjustment (the continuing vertical movement of land in response to the melting of the ice cover from the last ice age), sediment compaction, and groundwater and fossil fuel withdrawals.

These global and regional/local scenario products are available for the 2000–2100 period at 10-year intervals and over 2100–2200 at a coarser temporal resolution (the scenario values are provided for 2120, 2150, and 2200).

Population and Land-Use Scenarios

Population and land-use scenarios for NCA4 have been developed through the U.S. Environmental Protection Agency's (EPA) Integrated Climate and Land Use Scenarios (ICLUS) effort. ICLUS explores future changes in human population and developed land use for the contiguous United States. These projections are broadly consistent with peer-reviewed storylines of population growth and economic development that are now widely used by the climate change impacts community.[10] Specifically, the different population and land-use change scenarios stem from global population and urbanization assumptions underlying two

different future trajectories from the Shared Socioeconomic Pathways (SSPs) effort:[11] SSP2, which represents a business-as-usual trajectory, similar to the U.S. Census population projection (out to 2060), and SSP5, which represents a trajectory with higher fertility and higher net migration into the United States.[12] At the global scale, socioeconomic assumptions under SSP2 are broadly consistent with the concentration pathway and resultant radiative forcing for RCP4.5, whereas the socioeconomic assumptions under SSP5 are more consistent with RCP8.5.

ICLUS data (version 2) outputs have been made available to NCA4 authors (including training webinars) and consist of both population and land-use projections. Two ICLUS projections are provided. These are based on the 2010 U.S. Census and use fertility, mortality, and immigration rates from the Wittgenstein Centre to project decadal population to 2100, consistent with the demographic assumptions of the SSP2 and SSP5 socioeconomic scenarios, respectively.

These ICLUS population projections are used as inputs to a land-use model, which spatially allocates five residential land uses (exurban-low, exurban-high, suburban, urban-low, and urban-high) as well as commercial and industrial uses.

Indicators

Overview

The USGCRP hosts an interagency climate-related indicator platform at http://www.globalchange.gov/browse/indicators. Climate indicators for this purpose are defined as observations or other measures that are used to track the state of or the trend in conditions with a scientifically based relationship to the changing climate. For example, businesses might look at the unemployment index as one of a number of indicators representing the condition of the economy. Similarly, indicators related to climate—which may be physical, ecological, or societal—can be used to understand how environmental conditions are changing, to assess risks and vulnerabilities, and to help inform resilience and planning for climate impacts.

One of the primary goals of the USGCRP indicators effort is to support a sustained National Climate Assessment process by regularly tracking variables relevant to climate change. USGCRP and its participating agencies intend to maintain the indicators as a living resource, routinely updating them with new data. In addition, the indicators effort serves as a platform for USGCRP agencies to showcase data collection efforts and to highlight research related to indicators of change across a range of sectors.

The USGCRP indicators are not intended to be representative of all potential indicators across all possible scales; rather, they are meant to communicate several key aspects of climate change, such as temperatures over land and at sea, greenhouse gas (GHG) levels in the atmosphere, the extent of arctic sea ice, and related effects in sectors like public health, water resources, and agriculture. All of the indicators show climate-related trends over time and meet established criteria related to data quality.[13] Similar to the findings and figures in NCA3 and other NCA reports and products, the indicators' underlying datasets are documented in USGCRP's Global Change Information System (GCIS).

USGCRP Indicators

USGCRP's indicator platform currently includes 15 representative global and national-level climate indicators:[14]

- annual GHG index
- arctic glacial mass balance

- arctic sea ice extent
- atmospheric carbon dioxide
- frost-free season
- global surface temperatures
- heating and cooling degree days
- heavy precipitation
- ocean chlorophyll concentrations
- sea level rise (global)
- sea surface temperatures
- start of spring
- terrestrial carbon storage
- U.S. heat waves
- U.S. surface temperatures

Additional Indicator Resources

Several U.S. federal agencies make available climate-relevant indicators and their underlying data. For example, the EPA partners with more than 40 data contributors from various government agencies, academic institutions, and other organizations to compile a key set of nearly 40 indicators related to the causes and effects of climate change. The indicators are published in the EPA's report *Climate Change Indicators in the United States*. Updated datasets can be found on the EPA website.[17] To provide a more comprehensive resource to NCA4 authors and the broader public, readers can access a much more expansive suite of climate indicators, many at a regional scale, here: https://www.epa.gov/climate-indicators.

The EPA's climate indicators effort is meant to communicate the causes and effects of climate change in the areas of atmospheric composition, weather and climate, oceans, snow and ice, health and society, and ecosystems. All of the indicators are based on historical observations (no projections), are independently peer-reviewed, and are routinely updated with new data.

A variety of other readily accessible federal climate indicator resources are available for public use, including

- Centers for Disease Control and Prevention's (CDC) National Environmental Public Health Tracking network: https://ephtracking.cdc.gov/showClimateChangeIndicators,
- EPA's U.S. Inventory of Greenhouse Gas Emissions and Sinks: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks,
- National Aeronautics and Space Administration's (NASA) Global Climate Change: Vital Signs of the Planet: https://climate.nasa.gov/,
- National Oceanic and Atmospheric Administration's (NOAA) Arctic Program, Arctic Report Card: http://www.arctic.noaa.gov/Report-Card, and
- NOAA's State of the Climate: https://www.ncdc.noaa.gov/sotc/.

Other relevant sources of indicator information include

- NOAA's State Summaries: stateclimatesummaries.globalchange.gov, and
- USGCRP's *Climate Science Special Report*: https://science2017.globalchange.gov/.[18]

Climate Change Indicators

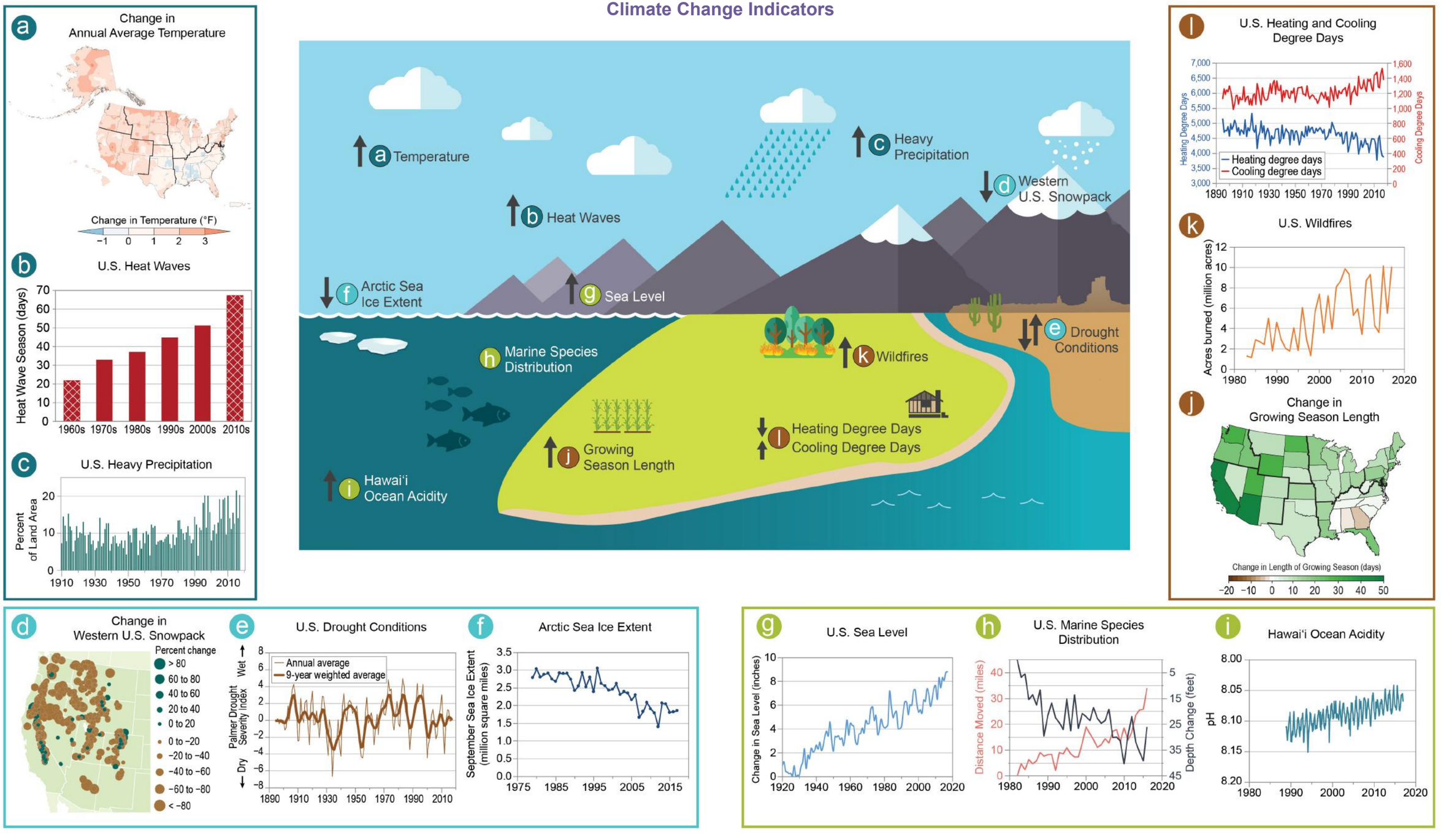

Figure A3.2: Long-term observations demonstrate the warming trend in the climate system and the effects of increasing atmospheric greenhouse gas concentrations (Ch. 2: Climate, Box 2.2). This figure shows climate-relevant indicators of change based on data collected across the United States. Upward-pointing arrows indicate an increasing trend; downward-pointing arrows indicate a decreasing trend. Bidirectional arrows (for example, for drought conditions) indicate a lack of a definitive national trend. (Figure caption continued on next page)

Atmosphere (a–c): (a) Annual average temperatures have increased by 1.8°F across the contiguous United States since the beginning of the 20th century; this figure shows observed change for 1986–2016 (relative to 1901–1960 for the contiguous United States and 1925–1960 for Alaska, Hawai'i, Puerto Rico, and the U.S. Virgin Islands). Alaska is warming faster than any other state and has warmed twice as fast as the global average since the mid-20th century (Ch. 2: Climate, KM 5; Ch. 26: Alaska, Introduction). (b) The season length of heat waves in many U.S. cities has increased by over 40 days since the 1960s. Hatched bars indicate partially complete decadal data. (c) The relative amount of annual rainfall that comes from large, single-day precipitation events has changed over the past century; since 1910, a larger percentage of land area in the contiguous United States receives precipitation in the form of these intense single-day events.

Ice, snow, and water (d–f): (d) Large declines in snowpack in the western United States occurred from 1955 to 2016. (e) While there are a number of ways to measure drought, there is currently no detectable change in long-term U.S. drought statistics using the Palmer Drought Severity Index. (f) Since the early 1980s, the annual minimum sea ice extent (observed in September each year) in the Arctic Ocean has decreased at a rate of 11%–16% per decade (Ch. 2: Climate, KM 7).

Oceans and coasts (g–i): (g) Annual median sea level along the U.S. coast (with land motion removed) has increased by about 9 inches since the early 20th century as oceans have warmed and land ice has melted (Ch. 2: Climate, KM 4). (h) Fish, shellfish, and other marine species along the Northeast coast and in the eastern Bering Sea have, on average, moved northward and to greater depths toward cooler waters since the early 1980s (records start in 1982). (i) Oceans are also currently absorbing more than a quarter of the carbon dioxide emitted to the atmosphere annually by human activities, increasing their acidity (measured by lower pH values; Ch. 2: Climate, KM 3).

Land and ecosystems (j–l): (j) The average length of the growing season has increased across the contiguous United States since the early 20th century, meaning that, on average, the last spring frost occurs earlier and the first fall frost arrives later; this map shows changes in growing season length at the state level from 1895 to 2016. (k) Warmer and drier conditions have contributed to an increase in large forest fires in the western United States and Interior Alaska over the past several decades.[15] (l) Degree days are defined as the number of degrees by which the average daily temperature is higher than 65°F (cooling degree days) or lower than 65°F (heating degree days) and are used as a proxy for energy demands for cooling or heating buildings. Changes in temperatures indicate that heating needs have decreased and cooling needs have increased in the contiguous United States over the past century. Sources: (a) adapted from Vose et al. 2017,[16] (b) EPA, (c–f and h–l) adapted from EPA 2016,[17] (g and center infographic) EPA and NOAA.

Climate Resilience Toolkit

In NCA3, authors used case studies to highlight specific examples of work being done by regions, cities, and stakeholders throughout the United States. These case studies formed some of the basis for the development of the U.S. Climate Resilience Toolkit (CRT).

The CRT is a free, open-source website (https://toolkit.climate.gov/) designed to help communities and businesses build resilience to climate-related impacts and extreme events. Its primary target audience is applied professionals—including city planners, resource managers, policy leaders, facility managers, analysts, and consultants—who oversee or help guide the development and implementation of climate adaptation plans. The site is easily understandable and is also accessible to the general public, a secondary target audience.

Published in November 2014, the CRT was developed as an interagency partnership under the auspices of the USGCRP. Hosted and managed by NOAA, it is a web-based framework that aggregates and contextualizes scientific information, tools, and expertise to help people

1. make and implement climate adaptation plans;
2. explore how climate conditions are changing in their location and understand how their valued assets are, or may be, impacted;
3. learn what others are doing to address climate-related challenges similar to the ones they face; and
4. learn about funding sources that can help in disaster recovery and/or to mitigate future risks.

Case studies (https://toolkit.climate.gov/#case-studies) have also been incorporated as a feature of NCA4, and some of those studies will be incorporated into the CRT in the future.

Steps to Resilience

The CRT's "Steps to Resilience" is the site's centerpiece (https://toolkit.climate.gov/#steps). It is a five-step, iterative risk-management framework that integrates a range of different content types into topical, geographical, and purposeful frames of reference.

This framework guides users through a deliberative process whereby they can access, explore, discuss, co-produce, and integrate information to build shared mental models as they address several fundamental questions:

1. Do climate-related hazards threaten assets we value?

2. If so, what is the risk, and are we willing to tolerate that level of risk?

3. If the risk is intolerable, what options exist to reduce or eliminate the risk?

4. Which options are viable and affordable, and in what priority order might we pursue them?

5. How will we plan and implement particular actions?

To help users answer these questions, the Toolkit offers plain language narratives—excerpted from the NCAs and other authoritative sources—that summarize ways that U.S. sectors, regions, and built and natural environments are vulnerable to, and have been impacted by, climate and non-climate stressors. These narratives are cross-linked with over 110 real-world case studies, from across the United States and its territories, highlighting people in communities and businesses who have successfully taken action to manage their climate risks. Additionally, the site's narratives and case studies are cross-linked with science-based decision support tools to illustrate how people have used those tools to plan and build resilience.

CRT Tools and the Climate Explorer

The CRT's "Tools" compendium (https://toolkit.climate.gov/tools) has more than 400 decision support tools offering a wide range of functions, such as helping people identify their vulnerabilities, view past and present climate conditions, download and analyze data, engage and communicate, check applied forecasts, find adaptation planning support, recover and rebuild from a disaster, and visualize climate projections.

The "Climate Explorer" (https://toolkit.climate.gov/#climate-explorer) is the CRT's featured tool for visualizing climate projections. Maps and graphs are available for 20 decision-relevant variables (such as temperature, precipitation, and heating- and cooling-degree days) for every county in the contiguous United States. Users can compare observed historical data to hindcasts (a method of testing a model for future events by comparing predictions of past events to known data) for the 1950–2006 period, and they can explore the projected rates and magnitudes of change in two future scenarios (RCP4.5 and RCP8.5) from 2006-2100.

Climate Explorer version 2.6, published in May 2018, features these improvements:

- replaced the Bias Corrected Constructed Analogs (BCCA) with the LOcalized Constructed Analogs (LOCA) projection dataset to align with the NCA4;

- added about 90 tidal stations charting both historical observed and future projected annual number of days with high tide flooding;
- enabled users to visually compare future projections to observed historical maps (1961–1990);
- added a new module enabling users to select specific thresholds for select locations to produce annual counts of observed threshold exceedance over time; and
- transitioned the tool's map library from OpenLayers to the ArcGIS Javascript library to make it interoperable with Esri's "ArcGIS Living Atlas of the World."

The CRT evolved and expanded in 2017 to include regional sections, enhancements to link more closely with the Steps to Resilience, and an expanded menu of climate variables offered in the Climate Explorer.

Climate Resilience Toolkit Case Study Categories

Climate Threat/Stressors	Topics	Resilience Steps	Regions
• Sea level rise, storm surge, and coastal flooding • Drought • Extreme precipitation • General climate change • Extreme events • Increased temperatures • El Niño, La Niña, and climate variability • Flooding • Changes in growing seasons • Changing ocean conditions • Reduced sea ice, permafrost, and snow • Temperature extremes	• Coasts • Built environment • Water • Ecosystems • Health • Food • Tribal nations • Marine • Energy • Transportation	1. Explore climate threats 2. Assess vulnerability and risks 3. Investigate options 4. Prioritize actions 5. Take action	• Southwest • Northeast • Southeast • Midwest • Alaska • Northwest • Hawai'i and U.S.-Affiliated Pacific Islands • Great Plains • International • National

Table A3.2. The CRT contains over 140 case studies, which users can quickly filter to locate a story of interest using the menu filters listed above.

Climate Resilience Toolkit Decision Support Tools

Topic	Tool Function
• Coasts • Built environment • Water • Ecosystems • Health • Food • Tribal nations • Marine • Energy • Transportation	• Identify vulnerabilities • View past and current conditions • Analyze and download data • Engage and communicate • Find adaptation planning support • Check applied forecasts • Recover and rebuild • Visualize climate projections

Table A3.3: The CRT contains over 400 decision support tools, and users can filter by topic, function, U.S. region, and the Steps to Resilience.

Global Change Information System

Summary

The National Climate Assessment and Development Advisory Committee (NCADAC), which guided the development of NCA3, recommended in 2013 that the NCA process "manage data to maximize utility and transparency."[19] The report also highlighted the importance of "developing a comprehensive web-based system to deploy and manage global change information and present it in a way that can be used by and benefit scientists, the public, and decision-makers." To achieve these goals, the USGCRP established the Global Change Information System (GCIS).

The GCIS is an open-source centralized database of all materials and data used for USGCRP assessments (https://data.globalchange.gov/). The system acts as an advanced, multifaceted bibliography, maintaining traceable provenance records of scientific information and providing access to the original data and research. The GCIS catalogs the cross-links among research papers, researchers, original data, and more and includes links back to authoritative sources for its information. GCIS serves as a key supporting resource for assessments produced by the USGCRP, providing information about the data underpinning them. In addition, the GCIS guides users to global change research produced by the 13 USGCRP member agencies.

Identifiers

Each item (for example, a report, dataset, or organization) referenced in the GCIS has a unique, persistent identifier. When possible, this includes or is related to third-party identification systems, such as Universally Unique Identifiers (UUIDs), Digital Object Identifiers (DOIs), Open Researcher and Contributor Identifiers (ORCIDs), and International Standard Book Numbers (ISBNs). This enhances interoperability between the GCIS and other information systems. For resources where such persistent identifiers are unknown, GCIS creates its own, and links between resources are assigned using the identifiers so that edits and corrections made to resource names or other properties do not break data linkages.

Provenance and Semantics

GCIS is built to represent the provenance of information contained in government assessments about global environmental change. GCIS includes in this (following the World Wide Web Consortium's definition of provenance) "information about entities, activities, and people involved in producing a piece of data or thing, which can be used to form assessments about its quality, reliability or trustworthiness."[20] This information is captured by a combination of documentation by the authors and scripts that ingest machine-readable metadata from online catalogs. Resources in GCIS are related both in relational databases, for cases of ownership (for example, a chapter belongs to a report and doesn't exist independently), and in a database that represents semantically the nature of the relationship between two resources (for example, a report *cites* a book, a table *is derived from* a dataset).

Traceability and Provenance in GCIS

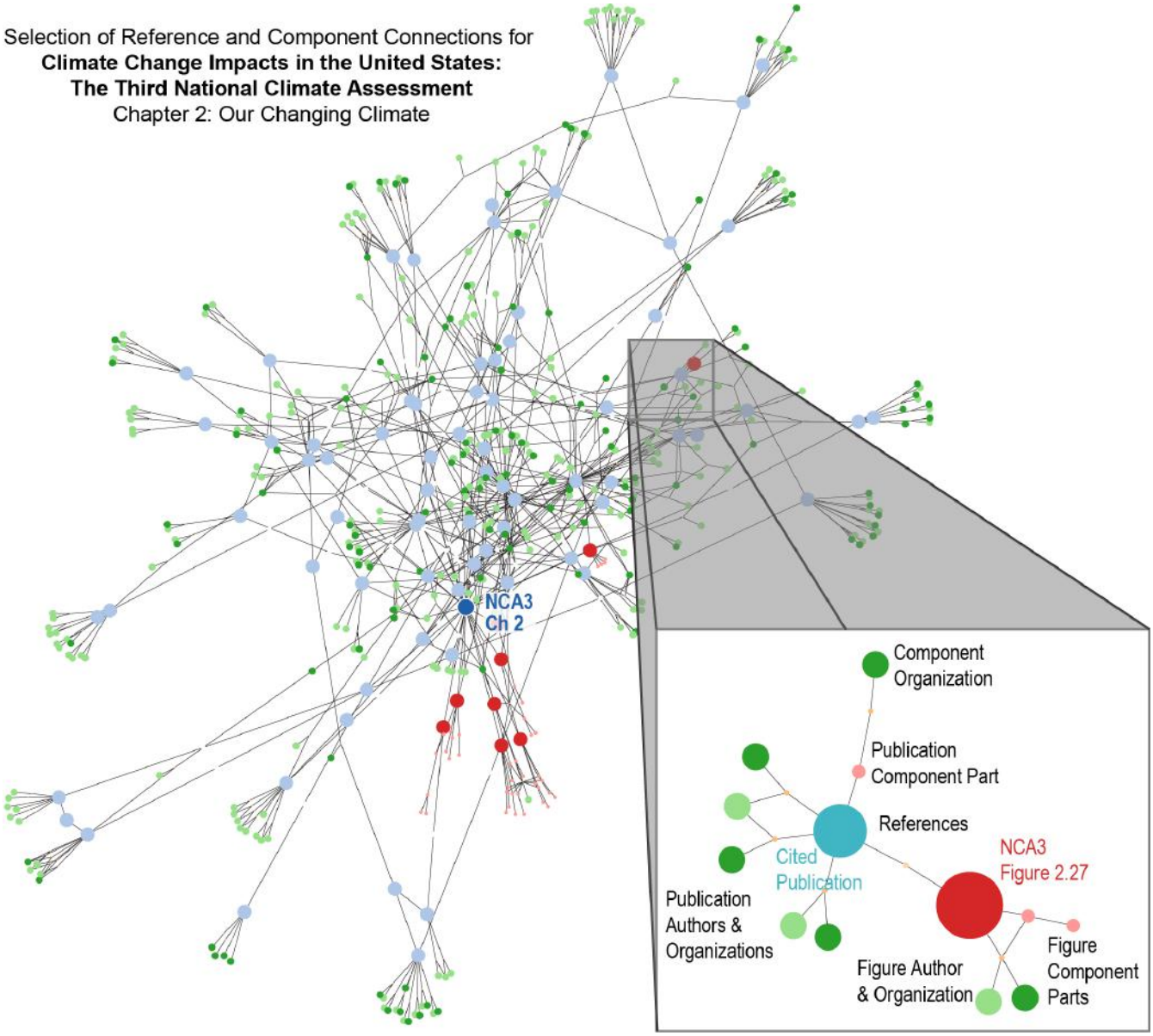

Figure A3.3: This figure is a graphic representation of traceability and provenance within the Global Change Information System (GCIS). All records within GCIS seek to have each component of this chain tracked and available to any reader. Tracking each of these components allows for any interested member of the public to trace a conclusion back to the supporting data for that conclusion. Source: USGCRP.

NOAA State Climate Summaries

Overview

NOAA produced a set of State Climate Summaries in response to a growing demand for state-level information after the release of NCA3 (stateclimatesummaries.globalchange.gov). These summaries consist of observed and projected climate change information and focus on aspects that are part of NOAA's mission (mainly, characteristics of the physical climate and coastal issues). These state summaries support various aspects of chapters throughout NCA4 and, deriving from the charge in the Global Change Research Act of 1990, contain information both on historical trends and scientific knowledge about potential future trends.

While the datasets and simulations in these state summaries are not by themselves new (they have been previously published in various sources), these documents represent a targeted synthesis of historical and plausible future climate conditions for each state.

Each summary consists of several high-level Key Messages about how climate change has or is likely to affect that state, as well as a description of the historical climate conditions in the state and of the climate conditions associated with future pathways of GHG emissions. In addition to this consistent information across all the state summaries, each summary contains some degree of state-specific information, making it uniquely valuable to decision-makers across the respective state. All 50 summaries (plus one for Puerto Rico and the U.S. Virgin Islands) underwent an anonymous external review, with at least two expert reviews completed per state.

Historical Climate

The description of historical climate conditions for each state is based on an analysis of core climate data (the data sources are described in the supplementary online material for the summaries). However, to help understand, prioritize, and describe the importance and significance of different climate conditions, additional input was derived from climate experts in each state, some of whom are authors on these state summaries. In particular, input was sought from the NOAA Regional Climate Centers and from the State Climatologists. The historical climate conditions are meant to provide a perspective on what has been happening in each state and what types of extreme events have historically been noteworthy and to provide a context for the assessment of future impacts.

Future Scenarios

Future climate scenarios are intended to provide an internally consistent set of climate conditions that can inform analyses of potential impacts of climate change under certain assumptions about the future pathway of GHG emissions. Here, "consistent" means that the relationships among different climate variables and the spatial patterns of these variables derive directly from the same set of climate model simulations and are, therefore, physically plausible. The future climate scenarios are based on well-established sources of information (see the Scenario Products section of this appendix). No new climate model simulations or downscaled datasets were produced for use in the state summaries.

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On the Web: https://nca2018.globalchange.gov/chapter/appendix-3

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A4 Appendix 4. Looking Abroad: How Other Nations Approach a National Climate Assessment

Introduction

The U.S. National Climate Assessment (NCA) is far from the only national assessment of climate impacts, risks, and adaptation in the world. There are a number of assessment products from other countries, each with its own distinct development process, structure, and intended purpose. This appendix is intended to place the Fourth National Climate Assessment (NCA4) within a broader international landscape of assessment activities and to compare it with other approaches.

The approach taken in this appendix has been to select a small set of assessment models from geographically varied nations with diverse capacities to conduct such assessments. Information on the assessment mandates and requirements, process, content structure, and international dimensions are included for each assessment. Because this appendix is intended to be illustrative rather than comprehensive, it does not summarize every report produced internationally—including, for example, the most recent climate assessment produced by the European Union.[1]

Selected National Climate Assessments

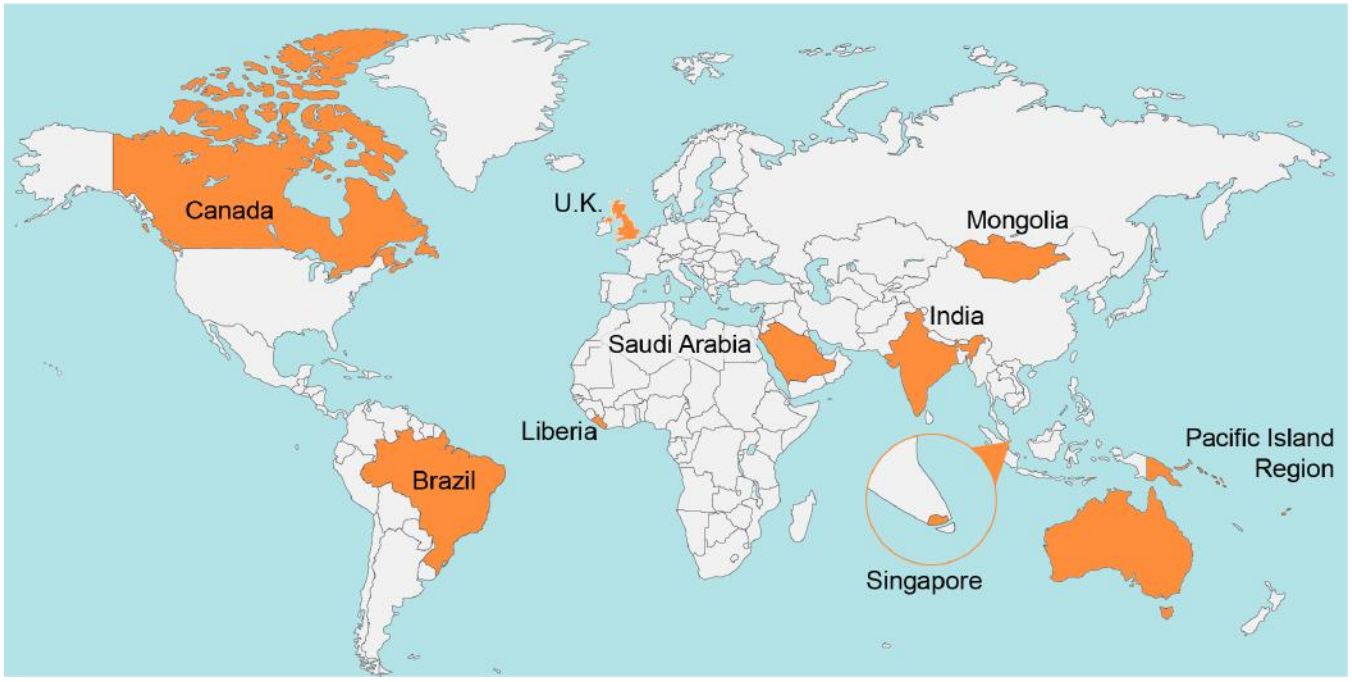

Figure A4.1: The U.S. National Climate Assessment represents one model for conducting national climate assessments, but there are many other national assessment models from countries around the world. Table A4.1 highlights key attributes for each national assessment model chosen for inclusion in this appendix, namely the assessment model type, a link to the assessment website, and the number of assessments to date (and the years they were completed). Source: USGCRP.

This appendix, one of several new additions to the NCA, was made in response to gaps identified in previous NCAs, as well as public input during the NCA4 scoping process—namely, to integrate the international context across NCA4 and, specifically, to include how NCA4 relates to complementary international assessment efforts. Therefore, in addition to this appendix, NCA4 includes a new national-level topic chapter focusing on U.S. international interests (see Ch. 16: International). The Hawai'i & U.S.-Affiliated Pacific Islands and (new) U.S. Caribbean regional chapters are intended to provide an entry point for Small Island Developing States (SIDS) to consider similarities in the risks they face and inform adaptation efforts within their own borders. Moreover, numerous case studies embedded throughout the report examine transboundary and international trade and economic issues.

Table A4.1: Summary of Assessment Models by Country

Nation(s)	Assessment Model	Number of Assessments to Date
Brazil	Not mandated by law, developed by a scientific panel established by ministerial ordinance, and modeled after IPCC assessment reports. http://www.pbmc.coppe.ufrj.br/en/	1 assessment (2013)
Canada	Not mandated by law, developed by federal government departments and modeled after the NCA4. http://www.nrcan.gc.ca/environment/impacts-adaptation/10029	6 assessments (1998, 2008 [2], 2014, 2016, 2017)
India	Not mandated by law, developed by domestic research institutions established by ministerial ordinance. http://www.moef.nic.in/division/indian-network-climate-change-assessment	1 assessment (2010)
Liberia	Not mandated by law, developed with U.S. support to fill knowledge gaps resulting from intra-national conflict. https://www.researchgate.net/publication/237102310_liberia_climate_change_assessment	1 assessment (2013)
Mongolia	Not mandated by law, developed by ministerial climate change office. http://www.jcm-mongolia.com/wp-content/uploads/2015/11/MARCC-Final-Bk-2014-book-lst.9.17-ilovepdf-compressed.pdf	2 assessments (2009, 2014)
Pacific Islands	Not mandated by law, developed as a collaborative regional-scale assessment between Australian agencies and Pacific countries. https://www.pacificclimatechangescience.org/publications/reports/	1 assessment (2011)
Saudi Arabia	Not mandated by law, voluntarily developed by national government as part of UNFCCC reporting requirements. http://www.cdmdna.gov.sa/report/40/third-national-communication-of-the-kingdom-of-saudi-arabia	3 assessments (2005, 2011, 2016)
Singapore	Not mandated by law, commissioned by government, and developed by a mixed team of national and international partners. http://ccrs.weather.gov.sg/Publications-Second-National-Climate-Change-Study-Science-Reports/	1 assessment (2015)
United Kingdom	Mandated by law, developed by a statutory independent committee. https://www.theccc.org.uk/tackling-climate-change/preparing-for-climate-change/uk-climate-change-risk-assessment-2017/	2 assessments (2012, 2017)

Federative Republic of Brazil[2,3]

Overview

Brazil released a National Assessment Report on Climate Change (RAN1) in 2013. The report was produced by a national scientific panel established by the government and was modeled on the Assessment Reports produced by the Intergovernmental Panel on Climate Change (IPCC). The RAN1 describes observed and projected impacts, assesses vulnerabilities in different national sectors and regions, and identifies options for adaptation measures. The report is intended to inform the development of the country's national planning activities related to climate change.

Assessment Mandate and Objectives

While Brazil does not have a nationally mandated climate assessment, the government has recognized the need for a national scientific body capable of providing policymakers at the federal, state, and local levels with objective information on the environmental, social, and economic effects of climate change. To this end, the Brazilian Panel on Climate Change (PBMC) was created in 2009 by a joint ordinance of the Ministry of the Environment and the Ministry of Science, Technology, Innovation and Communication.

The structure of the PBMC is based on the IPCC and includes a Steering Committee, Scientific Committee, Executive Secretariat, Working Groups, and Technical Support Units. The Panel is responsible for creating a range of policy-relevant products, including National Assessment Reports that provide a comprehensive scientific assessment of climate changes relevant to Brazil, Special Reports focusing on specific topics, and Technical Reports to help develop methods for monitoring and evaluating Brazil's greenhouse gas emissions. The PBMC represents the first national effort to consolidate and organize existing knowledge on climate change in Brazil onto a single platform. The Panel's report is intended to support the development and implementation of public policies such as the National Plan on Climate Change, Sectoral Mitigation and Adaptation Plans to Climate Change, and the National Adaptation Plan. As of October 2017, the RAN1 was the only national assessment report published by the Panel.

Assessment Process

Under the supervision of the PBMC's Steering Committee, the RAN1 report was written by approximately 100 scientists drawn from national research institutions and distributed across the Panel's three Working Groups (WGs), each of which composed a separate volume for the report. The Panel's Scientific Committee, composed of the coordinators of the WGs, developed the scope of each WG volume, coordinated the drafting of the report, and provided guidance to authors and reviewers throughout the process. The Panel's Steering Committee selected the authors through a public call, approved the Scientific Committee's proposed scoping for the report, approved the various drafts, and provided general direction for the Panel's work. At the end of the process, a Summary for Policy Makers was approved by the PBMC Plenary, which included the Steering and Scientific Committees' memberships, as well as representatives from federal and state governments. In the RAN1, the PBMC made use of the work of a range of observational and modeling research programs that have recently been developed in Brazil at the national and state levels.

Assessment Content Structure

The RAN1 report consists of three separate volumes, each of which is produced by one of the PBMC's three WGs and matches the structure of the IPCC Assessment Reports: Volume 1: The Scientific Basis of Climate Change; Volume 2: Impacts, Vulnerability and Adaptation; Volume 3: Mitigation of Climate

Change. Volume 1 surveys the current state of the scientific knowledge of climate change in Brazil and South America. Volume 2 evaluates the projected climate impacts and vulnerabilities across a range of natural systems, in five national regions (Northern, Northeast, Southern, Southeast, Center-West), and in key societal sectors (Rural and Urban communities, Energy, Industry, and Transportation). A topic receiving special focus is the impact of climate change on human health, well-being, and safety. Each volume was originally drafted in Portuguese but also has an accompanying Executive Summary in English.

International Dimensions

The RAN1 report does not explicitly consider the international dimensions of the impacts of climate change on Brazil. Some findings of the assessment were, however, incorporated into Brazil's 2016 National Communication, which it shared with the international community as part of its United Nations Framework Convention on Climate Change (UNFCCC) reporting requirements. The work of the PBMC is also intended to support international cooperation among developing countries and help countries build their capacity to respond to climate change through the sharing of assessment methodologies, the knowledge gained from these assessments, and Brazil's own national experiences with climate change. This is part of the PBMC's efforts to advance greater South–South dissemination and capacity building. The PBMC also received support from the British Government's Department for International Development.

Canada[4]

Overview

The government of Canada has completed six national-scale science assessments of climate change impacts and adaptation since 1998. Each assessment has included regional and/or sectoral analysis. Led by federal government departments, these assessments involved multiyear, collaborative processes that engaged academia, all levels of government, industry associations, Indigenous organizations, and the private sector. The current assessment process was launched in 2017 and will be completed in 2021.

Assessment Mandate and Objectives

National assessment products, rather than being nationally mandated, are deliverables of government programs supported though specific federal budget cycles. Assessment processes focus on the development and dissemination of products that synthesize and provide value-added analysis of the current state of knowledge. Assessments build awareness of the issues; inform research priorities, policy responses, and adaptation strategies; and enhance capacity to undertake adaptation. These goals are achieved through an inclusive, scientifically rigorous assessment process and the resulting reports.

Assessment Process

The lead federal department (currently, Natural Resources Canada) works with contributing departments to coordinate the assessment process and provide other secretariat functions. A multi-stakeholder advisory committee oversees the process and provides guidance and input throughout, from scoping to post-release. Subject matter experts are engaged as lead and contributing authors, while expertise in areas such as information technology and technical editing is contracted, as required. In addition, each assessment process includes extensive peer review to ensure accuracy and relevance. New elements of the current assessment process include a greater focus on communications, increased engagement of a broad range of Canadians, and the development of a suite of products that will be released over the assessment cycle, rather than just one large volume at the end.

Assessment Content Structure

Canadian assessments focus on climate change impacts and adaptation and draw from all relevant existing sources of knowledge (peer-reviewed publications, gray literature, Indigenous knowledge, and practitioner experience). Climate trends and projections for Canada are included to establish a robust, national overview of current and future changes in physical climate, in the context of informing the impacts and adaptation discussions. Since assessment activities are not legislated, there is flexibility in determining the content and structure, and these decisions take user needs into account. Past assessments have taken either a regional approach—addressing all major regions of Canada or a specific sensitive region (for example, marine coasts)—or a sectoral approach, focusing on a specific sector (for example, health or transportation) or multiple sectors within one volume. Increased engagement, interest, and resources have allowed the current assessment process to expand to include both regional and sectoral volumes, as well as stand-alone reports on climate trends and projections (led by Environment and Climate Change Canada) and on health issues (led by Health Canada).

International Dimensions

The 2008 assessment[5] included a chapter titled "Canada in an International Context." This chapter examined how climate change impacts on other countries, and their adaptation responses, could affect Canada. Sections focused on continental effects (North America), the surrounding oceans, and global impacts. The chapter also discussed Canada's international obligations on adaptation. The 2021 assessment will include a chapter on international dimensions that addresses transboundary issues, trade and supply chains, and linkages between adaptation, sustainable development, and disaster risk reduction globally.

Republic of India[6]

Overview

In 2010, India produced an assessment focused on a combined regional and sectoral analysis of climate change impacts through 2030. While not mandated by law, the federal government called for the assessment to be produced by domestic research institutions. The report represents the nation's first attempt to produce its own comprehensive climate impacts assessment and provides an integrated assessment of four primary regions and four primary sectors of key economic importance to the country. It focuses on observed and projected impacts and potential adaptation measures.

Assessment Mandate and Objectives

While India does not have a nationally mandated climate assessment, the government has stated the need for a comprehensive framework for assessing national- and state-level climate impacts, drawing from domestic technical and policy expertise. In 2009, the Ministry of Environment and Forests established the Indian Network for Climate Change Assessment (INCCA) to conduct research on climate drivers and impacts, prepare assessments of national vulnerability and adaptation, develop decision-support systems, and build capacity for the management of climate risks and opportunities. The broad purpose of the INCCA is to build an independent national research capacity for understanding and responding to climate change and to reduce dependence on external assessments and information sources.

Assessment Process

The INCCA brings together 125 research institutions and more than 250 scientists from across the country. The 2010 assessment report was prepared by 43 researchers from 18 separate institutions, led by the Ministry of Environment and Forests (now the Ministry of Environment, Forest and Climate Change). The Ministry also organized a series

of consultative meetings in 2009 and 2010 to inform the report's development. For the analysis of current and projected climate risks, the report utilized both historical observations and high-resolution climate projections using modeling tools obtained from the United Kingdom's Hadley Centre for Climate Prediction and Research.

Assessment Content Structure

The INCCA 2010 report is organized as a "4×4" assessment model that explores the impacts of climate change through the 2030s focused on four key climate-dependent sectors of the Indian economy (Agriculture, Water, Natural Ecosystems and Biodiversity, and Human Health) in four climate-sensitive regions (the Himalayan region, the Western Ghats, the Coastal Area, and the North-East region). The report provides an introduction to the INCCA framework, a discussion of regional climate observations and projections, an assessment of each sector and region, and an assessment of research needs moving forward.

International Dimensions

The INCCA 2010 report does not explicitly consider the international dimensions of the impacts of climate change on India. The findings of the assessment were, however, subsequently updated and incorporated into India's 2012 National Communication, which India shared with the international community through the UNFCCC. The reports were also produced using financial and technical support from international partners.

In January 2015, the United States and India created the Partnership for Climate Resilience. This Partnership aims to strengthen scientific cooperation on climate research and improve information available to decision-makers, building on the 2010 climate change assessment. Experts from the National Oceanic and Atmospheric Administration and academia, with support from the State Department, have partnered with Indian scientific experts and institutions to develop downscaled data for the Indian subcontinent at higher resolution than was previously available and to improve the capacity of local decision-makers to understand, predict, and plan for current and future impacts of climate variability and change.

Republic of Liberia[7]

Overview

In 2013, the U.S. Agency for International Development (USAID) Mission in Liberia commissioned the Republic of Liberia's Climate Change Assessment with involvement from the Liberian government. This international support provided Liberia with additional capacity to advance climate science data to the benefit of Liberian decision-makers. The assessment focused on potential climate change impacts on key Liberian natural resources and used refined downscaled modeling to produce data more targeted to the needs of Liberian decision-makers.

Assessment Mandate and Objectives

In March 2013, the Liberia USAID Mission produced Liberia's Climate Change Assessment to analyze natural resource vulnerabilities with respect to USAID climate change programs in the country. A key motivation for the report was to fill the knowledge gap caused by the loss of climate and environmental information during the country's civil wars. Its objectives were, broadly speaking, twofold: 1) assess the vulnerabilities of natural systems, and 2) provide a knowledge base to promote national climate resilience and improve the condition of rural subsistence farming communities.

Assessment Process

Although this assessment was not nationally mandated or produced by the national government, several Liberian agencies were engaged in developing the assessment in partnership

with U.S. federal agencies. It was prepared by the U.S. Department of Agriculture's Forest Service International Programs and reviewed by USAID. To achieve its objectives, the Liberia USAID Mission, in collaboration with the U.S. Forest Service, tasked a multidisciplinary team from the Forest Service Southern Research Station with conducting a climate change assessment. The team briefed Liberian agencies and civil society on the results. It also provided USAID and the Environmental Protection Agency of the Republic of Liberia with the modeled climate data and targeted training on how they might use the data.

Assessment Content Structure

The report focuses on the potential impacts of climate change on agriculture, fisheries, forests, energy, and mining. The assessment also touches on social vulnerability and the capacity of key segments of the Liberian population to adapt to current and projected climate change. It also examines the impacts on society from policy responses to climate change.

International Dimensions

This assessment was launched and largely conducted by an external international entity, namely USAID, though the Liberian government was involved in the process. The climate projections also utilized modeling tools and data obtained from the international community.

Mongolia[8]

Overview

The government of Mongolia has produced two Mongolia Assessment Reports on Climate Change (MARCC), in 2009 and 2014. The assessments are intended to serve as a definitive source of information on the latest research on climate change as it relates to Mongolia. This includes observed and projected climate changes; impacts on environmental, economic, and social sectors; and information on societal responses to climate change. The findings and recommendations of the MARCC reports are intended to feed into the country's national development programs and climate action plans.

Assessment Mandate and Objectives

While there is no explicit legal mandate for the MARCC, it does exist within an evolving national legal and policy framework to address climate challenges and meet Mongolia's obligations under international agreements on the environment and climate change. Under the country's revised Law on Air (2012), the Ministry of Environment and Tourism manages a Climate Change Coordination Office (CCCO), which implements Mongolia's commitments to the UNFCCC and integrates climate change issues into other national sectors. In addition, a National Action Programme on Climate Change (NAPCC), approved by Parliament in 2011, defines strategic objectives and outlines specific activities to integrate climate change concerns into national development plans and action plans. The MARCC 2014 report is intended to support the NAPCC by presenting the most current knowledge of observed and projected climate change. It does so by describing climate impacts on human and natural systems, highlighting strategies and technology needs for mitigation/adaptation measures, presenting a national greenhouse gas (GHG) inventory, and explaining the policy framework for climate action in Mongolia. The report is designed for use by a wide audience: government officials, policy- and decision-makers, members of professional societies and scientific communities, educators and students, and the general public.

Assessment Process

The MARCC 2014 report was prepared under the supervision of the chair of the CCCO, with logistical and technical support from CCCO staff. Financial support for preparation and

publication of the report was provided by the German development agency GIZ (German Corporation for International Cooperation) on behalf of the German Federal Ministry for Economic Cooperation and Development. Subject matter experts wrote each chapter. The document was originally drafted in Mongolian and then translated into English. In its presentation of current and projected climate change, MARCC 2014 made use of the IPCC's Fifth Assessment Report (AR5).

Assessment Content Structure

The MARCC 2014 report begins with basic information on observed and projected climate change in Mongolia, organized at the national and regional level. Subsequent chapters organize the impacts of climate change sectorally, on a range of natural and human systems. For natural systems, the report focuses on soil and pasture, forest ecosystems, fauna, water resources, natural disasters, land degradation and desertification, and dust/sand storms. For human systems, the report focuses on animal husbandry, agriculture, poverty and human development, infrastructure, and human health. Later chapters review adaptation options and possible mitigation measures, including a national GHG inventory and related technology issues. The final chapter covers policy frameworks, legal instruments, and institutional arrangements.

International Dimensions

While neither the MARCC 2009 nor the MARCC 2014 explicitly considers the international dimensions of climate change impacts on Mongolia, both reports do provide descriptions of the international policy setting within which Mongolia's climate change efforts exist. In particular, the MARCC 2014 describes in detail Mongolia's recent engagement with a range of international organizations to develop its domestic climate change policy and related interventions, in general. In addition, both the 2009 and 2014 MARCC reports were produced with financial and technical support from international partners.

Pacific Islands[9]

Overview

The Australian government published a Climate Change in the Pacific (CCP) report in 2011. The regional-level report provides a peer-reviewed scientific assessment of how the climate of the western Pacific region is changing. The report was produced through a collaboration between Australian government agencies and Pacific countries. It reviews current trends and projections of climate change for 14 Small Island Developing States (SIDS) and Timor-Leste, and identifies research and knowledge gaps in the region.

Assessment Mandate and Objectives

The significant research gaps identified in the IPCC's Fourth Assessment Report (AR4) served as the foundation for the creation of Australia's Pacific Climate Change Science Program (PCCSP). The objectives of the program are to conduct comprehensive climate change science, build capacity in partner countries across the Pacific to undertake scientific research, and disseminate information to partner countries' stakeholders and other parties. As part of Australia's five-year International Climate Change Adaptation Initiative, the PCCSP produced the Climate Change in the Pacific report in 2011. The report is intended to help countries in the Pacific prioritize adaptation measures, assess their vulnerability, develop adaptation strategies, and address research gaps described in the IPCC's AR4.

Assessment Process

The PCCSP is a collaborative research partnership among Australian government agencies, 14 Pacific Island countries, and Timor-Leste, as well as regional and international organizations. The 14 Pacific countries are the Cook

Islands, Federated States of Micronesia, Fiji, Kiribati, Marshall Islands, Nauru, Niue, Palau, Papua New Guinea, Sāmoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu. To ensure that research is of relevance to partner country decision-makers, coordinated information sharing, capacity building, and engagement have been conducted throughout all research areas and among all partner countries.

Assessment Content Structure

This report contains two volumes. The first provides a detailed assessment and analysis of changes in the observed and projected climate of the PCCSP region. The second includes climate change reports for each partner country. Each of the 15 reports includes sections on seasonal cycles, climate variability, observed annual trends, and projections for atmospheric and oceanic variables.

International Dimensions

Climate Change in the Pacific is a regional scientific assessment supported by the government of Australia that involves collaboration with multiple countries, both within the Pacific region and beyond it through the contributions of international organizations.

Kingdom of Saudi Arabia[10]

Overview

The government of the Kingdom of Saudi Arabia (KSA) has voluntarily produced three assessments of the nation's vulnerability to climate change. The most recent national vulnerability assessment was completed in 2016 and incorporated into the National Communication submitted by the KSA to satisfy its UNFCCC reporting requirements. The vulnerability assessments identify current and future climate-related impacts as well as potential adaptation measures in specific sectors. They also identify knowledge gaps to be addressed by future assessments.

Assessment Mandate and Objectives

While the KSA does not have a nationally mandated climate assessment, it is required, as part of its reporting obligations and commitments under the UNFCCC (Article 12 and subsequent decisions taken at Conferences of the Parties), to submit National Communications that provide certain information related to its greenhouse gas (GHG) emissions and the implementation of actions to address climate change. These reports provide the international community with a recent inventory of each Party's GHG emissions, a description of the policy initiatives that the country has taken to respond to and prepare for climate change, and any other information relevant to the implementation of its commitments under the UNFCCC. As part of this reporting, the KSA has included a national climate assessment in all of its National Communications, submitted in 2005, 2011, and 2016. These assessments analyze regional climate trends and projections and their impacts on a range of nationally important sectors.

Assessment Process

The KSA's most recent National Communication was produced by a Designated National Authority, in coordination with a team of academics, consultants, and other experts drawn from relevant government ministries, research institutions, and other organizations. In particular, the General Authority of Meteorology and Environmental Protection (the Kingdom's environmental agency) and the Ministry of Energy, Industry and Mineral Resources played important roles in its development. The report was produced with assistance from the national oil and gas company (Saudi Aramco), the United Nations Environment Programme, and the Global Environment Facility. For the analysis of current and projected climate risks, the report utilized historical observations and high-resolution climate projections using modeling tools obtained from the United

Kingdom's Hadley Centre for Climate Prediction and Research.

Assessment Content Structure

Within the KSA's Third National Communication, the climate assessment component includes a chapter focusing on climate science, describing baseline conditions, recent trends, and future climate scenarios, as well as the methodologies employed and climate model outputs. Subsequent sectoral chapters describe vulnerabilities and identify national adaptation measures covering the areas of water resources, desertification, agriculture and food security, and human health. Each of these chapters offers more detailed and technical discussion of the sectoral impacts as well as recommendations for future research to address information and data gaps.

International Dimensions

The KSA's National Communications have not explicitly considered the international dimensions of climate change impacts on the country. The reports reflect the country's ongoing engagement with the UNFCCC process for assessing climate-related risks and developing policies to address them. The reports were also produced using financial and technical support from international partners.

Republic of Singapore[11]

Overview

The Republic of Singapore's National Climate Change Studies are voluntary reports, commissioned by the government and produced by a mixed team of national and international partners. Singapore has undertaken two studies, the first of which was completed in 2015 and the second of which is currently underway and will include a vulnerability analysis.

Assessment Mandate and Objectives

The National Environment Agency of Singapore (NEA) commissioned the current National Climate Change Study in recognition of the island nation's increasing vulnerability to climate change. The purpose is to assess the current and projected impacts from climate change, focusing on variables of greatest importance to the country (temperature, precipitation, and sea level), and to assess the vulnerability of various sectors to a changing climate. The results of the study will feed into the next stage of Singapore's national adaptation planning efforts.

Assessment Process

The NEA leads the development of the study, which is divided into two phases. Phase 1, which was published in 2015, provided long-term climate projections, while Phase 2, currently under development, will assess the vulnerability of Singapore's population, environment, and infrastructure to a changing climate. The work on Phase 1 was performed jointly by experts from the Centre for Climate Research Singapore and the Met Office Hadley Centre in the United Kingdom, with contributions from partners at the Australian Commonwealth Scientific and Industrial Research Organisation and the United Kingdom's National Oceanography Centre–Liverpool. The focus of the Phase 1 study was to produce high-resolution regional climate and sea level projections that extend to 2100. To ensure that outcomes from the study would be of use to decision-makers, stakeholder engagement was integrated early on in the process, with representatives from a range of national agencies taking part. In particular, engagement activities involved stakeholders' focusing on six thematic clusters: coastal protection; water resources and drainage; public health; network infrastructure; building, structure, and town infrastructure; and biodiversity and greenery.

Assessment Content Structure

The Phase 1 report of Singapore's Second National Climate Change Study is made up

of 10 primary chapters, each focusing on a specific element of the modeling process that generated the high-resolution projections to be used in the vulnerability assessment. The report also includes detailed technical appendices and supplementary information.

International Dimensions

Phase 1 of the current study was completed in close partnership with the United Kingdom and Australia. Additionally, the foundation for its scientific assessment stemmed from work conducted by the IPCC. The completed study will not explicitly consider international effects.

United Kingdom[12]

Overview

The government of the United Kingdom (UK) is legally required to produce a Climate Change Risk Assessment (CCRA) every five years and then develop National Adaptation Programmes to address those risks and build resilience to climate change. The core component of the CCRA is an independently produced Evidence Report that assesses climate risks and impacts in the UK. The Evidence Report feeds into a high-level Synthesis Report that identifies key areas of climate risk to be prioritized for action. The government evaluates this Synthesis Report and produces its final Risk Assessment, which is presented to Parliament. The most recent Evidence Report was developed using a risk-based framing and explicitly considers the international dimensions of climate impacts to the UK.

Assessment Mandate and Objectives

The 2008 Climate Change Act requires the UK government to present a CCRA to Parliament every five years. The purpose of the assessment is to evaluate the risks that current and predicted climate change impacts pose to the UK and, ultimately, to guide the development of National Adaptation Programmes for the UK and its component countries (the administrations of England, Northern Ireland, Scotland, and Wales).

Assessment Process

Under the 2008 Climate Change Act, two CCRAs have been completed, one in 2012 and the most recent in 2017. The Act establishes an independent body, the Committee on Climate Change, whose Adaptation Sub-Committee (ASC) was responsible for the CCRA Evidence Report and Synthesis Report in 2017. The Evidence Report summarizes the current state of knowledge of climate risks and opportunities in the UK and identifies priority areas needing urgent further action over the next five years. For the most recent Evidence Report, the ASC convened teams of experts to assess a wide range of climate risks and opportunities and assign urgency scores to inform national adaptation planning. The analysis was supplemented by several specially commissioned research studies on specific climate impacts and was informed by engagement with and review by stakeholders inside and outside of the government and across all four UK countries. The Synthesis Report, authored by the ASC, summarizes the Evidence Report and then identifies six areas of risk to be managed as priorities for the next five years. For the most recent CCRA, the government largely approved the conclusions from the various products of the ASC, which it produced in its final UK Climate Change Risk Assessment 2017.

Assessment Content Structure

The most recent Evidence Report includes multiple individual products. The main report is an independent analysis authored by academics, consultants, and other experts in the public and private sectors, as well as civil society organizations throughout the UK. It reviews evidence for current and future climate change in the UK, provides a description of the assessment methodology, and includes

technical chapters focused on specific sectors. Separate national summaries, authored by the ASC, present evidence specific to Scotland, England, Northern Ireland, and Wales.

International Dimensions

The CCRA Evidence Report has expanded since its inception to examine impacts at increasingly wider scales, both across sectors and geographically. While the focus of the first report was on a limited set of direct impacts within the UK, the most recent CCRA also considers the impacts on the UK from international effects, both direct (for example, through disruption of trade and supply chains) and indirect (for example, through price volatility of imported commodities). These topics are explored in a dedicated international dimensions chapter.

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A5 Appendix 5. Frequently Asked Questions

This appendix is an update to the frequently asked questions (FAQs) presented in the Third National Climate Assessment (NCA3). New questions based on areas of emerging scientific inquiry are included alongside updated responses to the FAQs from NCA3. The answers are based on the U.S. Global Change Research Program's (USGCRP) sustained assessment products, other peer-reviewed literature, and consultation with experts.

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Introduction to Climate Change

How do we know Earth is warming?

Many indicators show conclusively that Earth has warmed since the 19th century. In addition to warming shown in the observational record of oceanic and atmospheric temperature, other evidence includes melting glaciers and continental ice sheets, rising global sea level, a longer frost-free season, changes in temperature extremes, and increases in atmospheric humidity, all consistent with long-term warming.

Observations of surface temperature taken over Earth's land and ocean surfaces since the 19th century show a clear warming trend. Temperature observations have been taken consistently since the 1880s or earlier at thousands of observing sites around the world. Additionally, instruments on ships, buoys, and floats together provide a more-than-100-year record of sea surface temperature showing that the top 6,500 feet of Earth's ocean is warming in all basins.[1] These observations are consistent with readings from satellite instruments that measure atmospheric and sea surface temperatures from space. Used together, land-, ocean-, and space-based temperature observations show clear evidence of warming at Earth's surface over climatological timescales (http://www.globalchange.gov/browse/indicators for more indicators of change) (see also Ch. 2: Climate).

Scientists around the world have been measuring the extent and volume of ice contained in the same glaciers every few years since 1980. These measurements show that, globally, there is a large net volume loss in glacial ice since the 1980s. However, the rate of the ice loss varies by region, and in some cases yearly glacier advances are observed (see FAQ "How does climate change affect mountain glaciers?"). Ice sheets on Antarctica and Greenland have been losing ice mass consistently since 2002, when advanced satellite measurements of their continental ice mass began (see FAQ "Is Antarctica losing ice? What about Greenland?"). Arctic sea ice coverage has been monitored using satellite imagery since the late 1970s, showing consistent and large declines in September, the time of year when the minimum coverage occurs.[2]

There are additional observational lines of evidence for warming. For example, the area of land in the Northern Hemisphere covered by snow each spring is now smaller on average than it was in the 1960s.[3] Tide gauges and satellites show that global sea level is rising, both as a result of the addition of water to the ocean from melting glaciers and from the expansion of seawater as it warms (Ch. 2: Climate; Ch. 8: Coastal). Lastly, as air warms, its capacity to hold water vapor increases, and measurements show that atmospheric humidity is increasing around the globe, consistent with a warming climate (see Ch. 3: Water; see also Ch. 1: Overview, Figure 1.2 for more indicators of a warming world).

What makes recent climate change different from warming in the past?

Increases in global temperature since the 1950s are unusual for two reasons. First, current changes are primarily the result of human activities rather than natural physical processes. Second, temperature changes are occurring much faster than they did in the past.

Our planet's climate has changed before. Sedimentary rocks and fossils show clear evidence for a series of long cold periods—called ice ages—followed by warm periods. Common archaeological and geological processes for dating past events show that these cycles of cooling and warming occurred about once every 100,000 years for at least the last million years.

Before major land-use changes and industrialization, changes in global temperature were caused by natural factors, including regular changes in Earth's orbit around the sun, volcanic eruptions, and changes in energy from the sun.[4] Major warming and cooling events were driven by natural variations of Earth's orbit that altered the amount of sunlight reaching Earth's Arctic and Antarctic regions, resulting in the retreat and advance of massive ice sheets. Additionally, quiescent or active periods of volcanic eruptions also could contribute to warming or cooling events, respectively.[5]

Natural factors are still affecting the planet's climate today (see Figure A5.5). Yet since the beginning of the Industrial Revolution, human use of coal, oil, and gas has rapidly changed the composition of the atmosphere (Figure A5.1). Land-use changes (such as deforestation), cement production, and animal production for food have also contributed to the increase in levels of greenhouse gases in the atmosphere. Unlike past changes in climate, today's warming is driven primarily by human activity rather than by natural physical processes (see Figure A5.5) (see also Ch. 2: Climate).

Current warming is also happening much faster than it did in the past. Scientific records from ice cores, tree rings, soil boreholes, and other "natural thermometers"—often called proxy climate data—show that the recent increase in temperature is unusually rapid compared to past changes (see Figures A5.2 and A5.4). After an ice age, Earth typically took thousands of years to warm up again; the observed rate of warming over the last 50 years is about eight times faster than the average rate of warming from a glacial maximum to a warm interglacial period.[4]

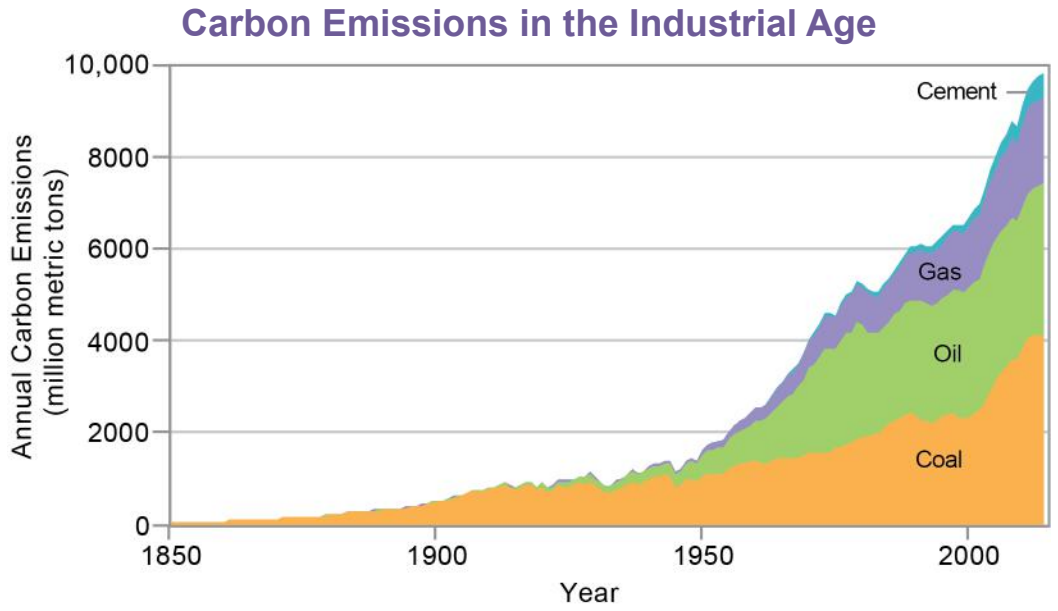

Figure A5.1 Humans have changed the atmosphere by burning coal, oil, and gas for energy and by producing cement. This graph shows the total global carbon emissions from these activities from 1850 to 2009. A range of other human activities, such as cutting down forests and livestock production, account for additional carbon emissions. Source: Walsh et al. 2014.[6]

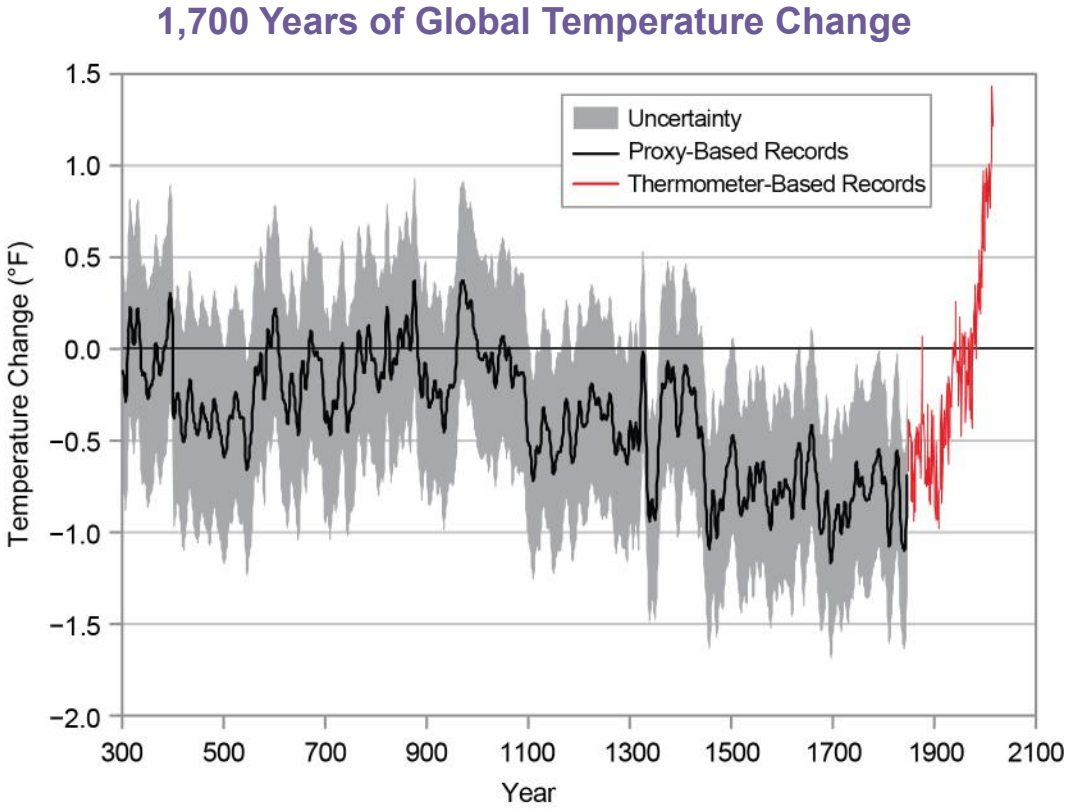

Figure A5.2 Average global temperature has increased rapidly over the last 1,700 years compared to the 1961–1990 average. The red line shows temperature data based on surface observations. The black line shows temperature data from proxies, including data from tree rings, ice cores, corals, and marine sediments. The comparison of proxy- and thermometer-based records suggests that temperatures are now higher than they have been in at least 1,700 years. The steep portion of the graph since about 1950 shows how rapidly temperature has increased compared to previous changes. Source: adapted from Mann et al. 2008.[7]

What's the difference between global warming and climate change?

Though some people use the terms "global warming" and "climate change" interchangeably, their meanings are slightly different. Global warming refers only to Earth's rising surface temperature, while climate change includes temperature changes and a multitude of effects that result from warming, including melting glaciers, increased humidity, heavier rainstorms, and changes in the patterns of some climate-related extreme events.

By itself, the phrase global warming refers to increases in Earth's annual average surface temperature. Today, however, when people use the phrase, they usually mean the recent warming that is due in large part to the rapid increase of greenhouse gases (GHGs) in the atmosphere from human activities such as deforestation and the burning of fossil fuels for energy. Thus, "global warming" has become a form of shorthand for a complex scientific process.

The entire globe is not warming uniformly. Some areas may cool (such as the North Atlantic Ocean), while some may warm faster than the global average (such as the Arctic). The term climate change refers to the full range of consequences or impacts that occur as atmospheric levels of GHGs rise and different parts of the earth system respond to a higher average surface temperature. For instance, observed long-term trends, such as increases in the frequency of drought and heavy precipitation events, are not technically warming trends, but they are related to current warming and are processes of climate change (Ch 2: Climate).

Climate Science

What are greenhouse gases, and what is the greenhouse effect?

Greenhouse gases (GHGs) are gases that absorb and emit thermal (heat) infrared radiation. Carbon dioxide, methane, nitrous oxide, ozone, and water vapor are the most prevalent GHGs in Earth's atmosphere. These gases absorb heat emitted by Earth's surface and re-emit that heat into Earth's atmosphere, making it much warmer than it would be otherwise—a process known as the greenhouse effect.

Most of Earth's atmosphere is made up of nitrogen (N_2) and oxygen (O_2), neither of which is considered a greenhouse gas. Other gases, known as greenhouse gases (GHGs), behave very differently from O_2 and N_2 when it comes to infrared radiation emitted from Earth. GHGs, such as water vapor, carbon dioxide (CO_2), and methane (CH_4), have a more complex molecular structure (made up of three or more atoms, as opposed to the symmetrical, two-atom molecules of O_2 and N_2) that absorbs some of the energy emitted from Earth's surface and then re-radiates that energy in all directions, including back down towards the surface. This ultimately traps energy in the lower atmosphere in the form of heat (Figure A5.3). This greenhouse effect makes the average temperature of Earth nearly 60°F warmer than it would be in the absence of these GHGs. Even a tiny amount of these gases can have a huge effect on the amount of heat trapped in the lower atmosphere, just like a tiny amount of anthrax can have a huge effect on human health.

Many GHGs, including CO_2, CH_4, water vapor, and nitrous oxide (N_2O), occur naturally in the atmosphere. However, atmospheric concentrations of these GHGs have been rising over the last few centuries as a result of human activities. In addition, human activities have added new, entirely human-made GHGs to the atmosphere, including chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6).[5]

As the global population has increased, so have GHG emissions. This in turn makes the greenhouse effect stronger, resulting in higher average temperature around the globe (Ch 2: Climate).

The Greenhouse Effect

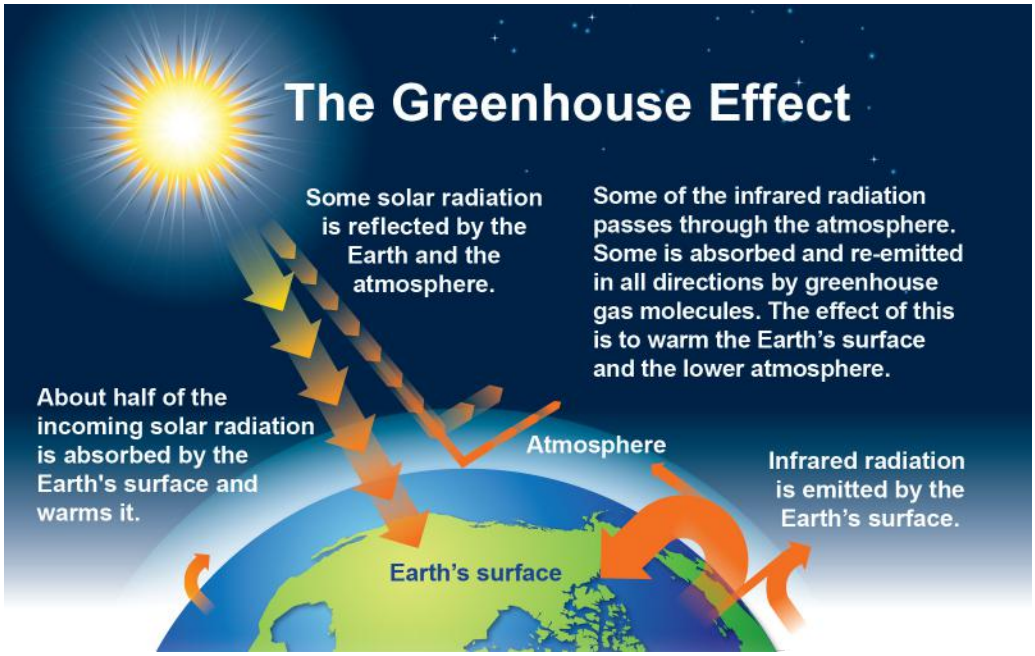

Figure A5.3: The figure shows a simplified representation of the greenhouse effect. About half of the sun's radiation reaches Earth's surface, while the rest is reflected back to space or absorbed by the atmosphere. Naturally occurring greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), do not absorb most of the incoming shortwave (visible) energy from the sun, but they do absorb the longwave (infrared) energy re-radiated from Earth's surface. This energy is then re-emitted in all directions, keeping the surface of the planet much warmer than it would be otherwise. Human activities—predominantly the burning of fossil fuels (coal, oil, and gas)—are increasing levels of CO_2 and other GHGs in the atmosphere, which is amplifying the natural greenhouse effect and thus increasing Earth's temperature. Source: adapted from EPA 2016.[8]

Why are scientists confident that human activities are the primary cause of recent climate change?

Many independent lines of evidence support the finding that human activities are the dominant cause of recent (since 1950) climate change. These lines of evidence include changes seen in the observational records that are consistent with our understanding, based on physics, of how the climate system should change due to human influences. Other evidence comes from climate modeling studies that closely reproduce the observed temperature record.

The Climate Science Special Report[9] concludes, "human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming since the mid-20th century." The Earth's climate only warms or cools significantly in response to changes that affect the balance of incoming and outgoing energy. Over long timescales (tens to hundreds of thousands of years), orbital cycles produce long periods of warming and cooling. Over shorter timescales, two factors could generally force changes in Earth's temperature to a measurable degree: (1) changes in the amount of energy put out by the sun, and (2) changes in the concentrations of greenhouse gases (GHGs) in Earth's atmosphere. Recent measurements of the sun's energy show no trend over the last 50 years. Additionally, observations show that the lower atmosphere (troposphere) has warmed while the upper atmosphere (stratosphere) has cooled. If the observed warming had been due to an increase in energy from the sun, then all layers of Earth's atmosphere would have warmed, which is not what scientists observe. Thus, we can eliminate changes in the energy received from the sun as a major factor in the warming observed since about 1950.[10]

This leaves the possibility that changes in GHG concentrations in the atmosphere are the primary cause of recent warming. Atmospheric carbon dioxide (CO_2) levels have increased from approximately 270 parts per million (ppm) during preindustrial times to the current 408 ppm observed in 2018 (see https://www.esrl.noaa.gov/gmd/ccgg/trends/)—levels that exceed any observed over the past 800,000 years (Figure A5.4). In addition, atmospheric concentrations of other GHGs (including methane and nitrous oxide) have increased over the same period. This increase in GHG concentrations has coincided with the observed increase in global temperature. Scientists use methods that provide chemical "fingerprints" of the source of these increased emissions and have shown that the 40% increase in atmospheric CO_2 levels since the Industrial Revolution is due mainly to human activities (primarily the combustion of fossil fuels) and not due to natural carbon cycle processes.[5]

Other evidence attributing human activities as the dominant driver of observed warming comes from climate modeling studies. Computer simulations of Earth's climate based on historical data of observed changes in natural and human influences accurately reproduce the observed temperature record over the last 120 years. These results show that without human influences, such as the observed increases in GHG emissions, Earth's surface would have cooled slightly over the past half century. The only way to closely replicate the observed warming is to include both natural and human forcing changes in climate models (Figure A5.5). Thus, the observational record and modeling studies both point to human factors being the main cause for the recent warming (Ch.2: Climate).

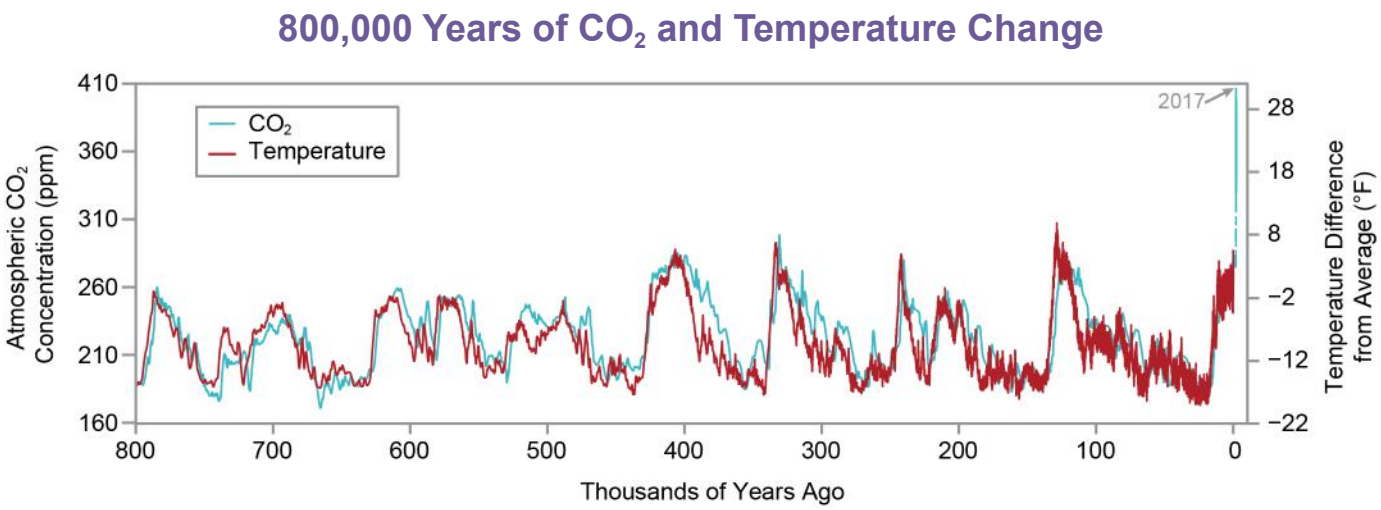

Figure A5.4: This chart shows atmospheric CO_2 concentrations (left axis, blue line) and changes in temperature (compared to the average over the last 1,000 years; right axis, red line) over the past 800,000 years, as recorded in ice cores from Antarctica. Also shown are modern instrumental measurements of CO_2 concentrations through 2017. Current CO_2 concentrations are much higher than any levels observed over the past 800,000 years. Source: adapted from EPA 2017.[11]

Human and Natural Influences on Global Temperature

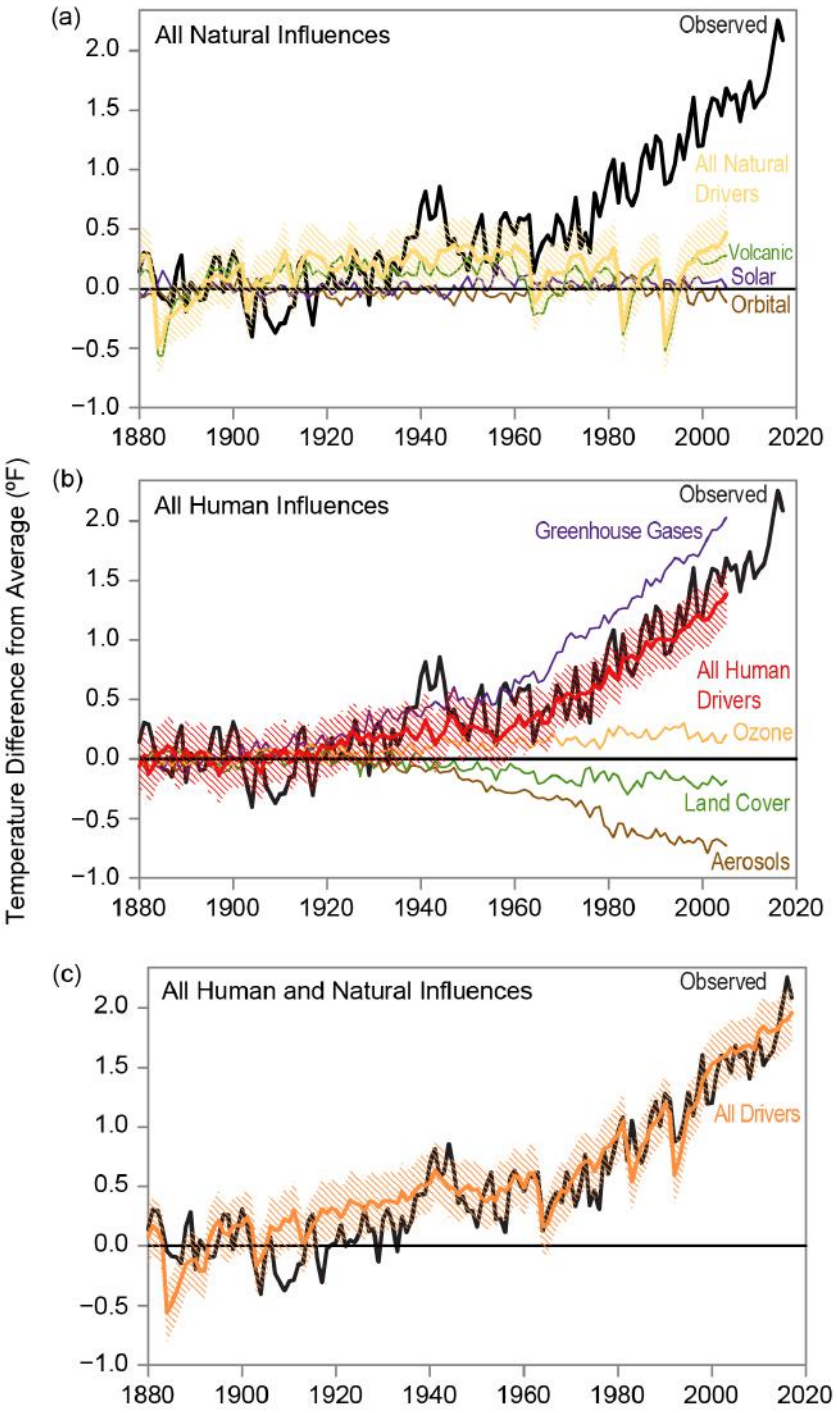

Figure A5.5: Both human and natural factors influence Earth's climate, but the long-term global warming trend observed over the past century can only be explained by the effect that human activities have had on the climate.

Sophisticated computer models of Earth's climate system allow scientists to explore the effects of both natural and human factors. In all three panels of this figure, the black line shows the observed annual average global surface temperature for 1880–2017 as a difference from the average value for 1880–1910.

The top panel (a) shows the temperature changes simulated by a climate model when only natural factors (yellow line) are considered. The other lines show the individual contributions to the overall effect from observed changes in Earth's orbit (brown line), the amount of incoming energy from the sun (purple line), and changes in emissions from volcanic eruptions (green line). Note that no long-term trend in globally averaged surface temperature over this time period would be expected from natural factors alone.[4]

The middle panel (b) shows the simulated changes in global temperature when considering only human influences (dark red line), including the contributions from emissions of greenhouse gases (purple line) and small particles (referred to as aerosols, brown line) as well as changes in ozone levels (orange line) and changes in land cover, including deforestation (green line). Changes in aerosols and land cover have had a net cooling effect in recent decades, while changes in near-surface ozone levels have had a small warming effect.[5] These smaller effects are dominated by the large warming influence of greenhouse gases such as carbon dioxide and methane. Note that the net effect of human factors (dark red line) explains most of the long-term warming trend.

The bottom panel (c) shows the temperature change (orange line) simulated by a climate model when both human and natural influences are included. The result matches the observed temperature record closely, particularly since 1950, making the dominant role of human drivers plainly visible.

Researchers do not expect climate models to exactly reproduce the specific timing of actual weather events or short-term climate variations, but they do expect the models to capture how the whole climate system behaves over long periods of time. The simulated temperature lines represent the average values from a large number of simulation runs. The orange hatching represents uncertainty bands based on those simulations. For any given year, 95% of the simulations will lie inside the orange bands. See Chapter 2: Climate for more information. Source: NASA GISS.

What role does water vapor play in climate change?

Water vapor is the most abundant greenhouse gas (GHG) in the atmosphere and plays an important role in Earth's climate, significantly increasing Earth's temperature. However, unlike other GHGs, water vapor can condense and precipitate, so water vapor has a short life span in the atmosphere. Air temperature, and not emissions, controls the amount of water vapor in the lower atmosphere. For this reason, water vapor is considered a feedback agent and not a driver of climate change.

Water vapor is the primary GHG in the atmosphere, and its contribution to Earth's greenhouse effect is about two or three times that of carbon dioxide (CO_2). Human activities directly add water vapor to the atmosphere primarily through increasing evaporation from irrigation, power plant cooling, and combustion of fossil fuels. Other GHGs, such as CO_2, are not condensable at atmospheric temperatures and pressures, so they will continue to build up in the atmosphere as long as their emissions continue.[12]

The amount of water vapor in the lower atmosphere (troposphere) is mainly controlled by the air temperature and proximity to a water source, such as an ocean or large lake, rather than by emissions from human activities. Fluctuations in air temperature change the amount of water vapor that the air can hold, with warmer air capable of holding more moisture. Increases in water vapor levels in the lower atmosphere are considered a "positive feedback" (or self-reinforcing cycle) in the climate system. As increasing concentrations of other GHGs (for example, carbon dioxide, methane, and nitrous oxide) warm the atmosphere, atmospheric water vapor concentrations increase, thereby amplifying the warming effect (Figure A5.6). If atmospheric concentrations of CO_2 and other GHGs decreased, air temperature would drop, decreasing the ability of the atmosphere to hold water vapor, further decreasing temperature.[5,12]

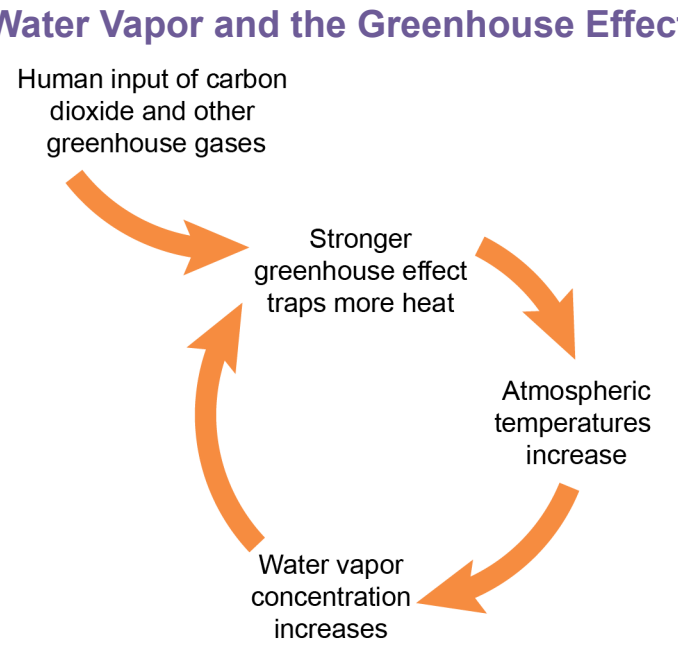

Figure A5.6: As emissions of carbon dioxide and other greenhouse gases increase, the strength of the greenhouse effect increases, which drives an increase in global temperature. This in turn increases the amount of water vapor in the lower atmosphere. Because water vapor is itself a greenhouse gas, the increase in atmospheric water vapor can further strengthen the greenhouse effect. Source: USGCRP.

How are El Niño and climate variability related to climate change?

El Niño and other forms of natural climate variability are not caused by humans, but their frequency, duration, extent, or intensity might be affected by greenhouse gas emissions from human activities. Natural climate variability produces short-term regional changes in temperature and weather patterns, whereas human-caused climate change is a persistent, long-term phenomenon.

Climate variability refers to the natural changes in climate that fall within the observed range of extremes for a particular region, as measured by temperature, precipitation, and frequency of events. Drivers of climate variability include the El Niño–Southern Oscillation (ENSO) and other phenomena. ENSO is a quasi-periodic warming or cooling of the of the sea surface temperatures in the tropical eastern Pacific and is often referred to by its phase of El Niño (warm phase) or La Niña (cool phase). These different ENSO phases can have varying ecosystem and economic effects, especially in certain fishing communities, while also influencing weather worldwide (Figure A5.7). In the United States, El Niño conditions generally correspond with warmer than average sea surface and air temperatures along the West Coast, wetter conditions in the Southwest, cooler temperatures in the Southeast, and warmer conditions in the Northeast. In contrast, the La Niña phase of ENSO corresponds to cooler temperature in the U.S. Northwest and dryer and warmer conditions in the Southeast, along with increased upwelling along the West Coast.

Evidence from paleoclimate records suggests that there have been changes in the frequency and intensity of ENSO events in the past. Human-caused climate change might also affect the frequency and magnitude of ENSO events and can exacerbate or ameliorate regional ENSO impacts. For example, if there is a strong La Niña event that results in dry conditions in the Southwest, those conditions may be exacerbated by additional drying due to climate change. ENSO is a complex phenomenon, but new research is shedding light on the many factors influencing how climate change affects the ENSO cycle.[13]

El Niño/La Niña Cause Short-Term Changes in Weather Patterns

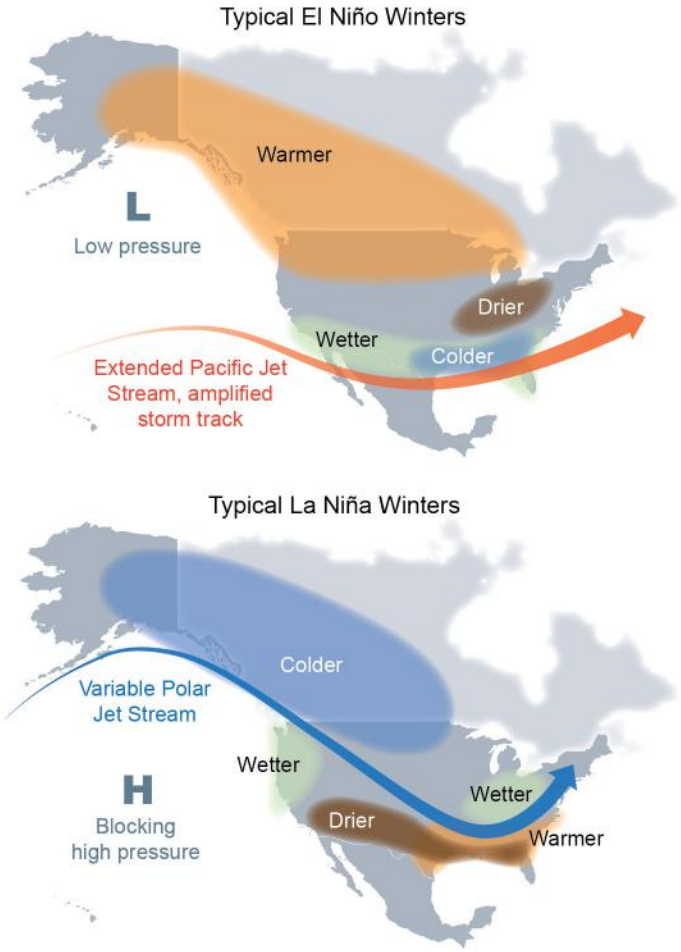

Figure A5.7: El Niño and La Niña events create different weather patterns during winters (January through March) over North America. (top) During an El Niño, there is a tendency for a strong jet stream and storm track across the southern part of the United States. The southern tier of Alaska and the U.S. Pacific Northwest tend to be warmer than average, whereas the southern United States tends to be cooler and wetter than average. (bottom) During a La Niña, there is a tendency for very wave-like jet stream flow over the United States and Canada, with colder and stormier than average conditions across the North and warmer and less stormy conditions across the South. Source: Perlwitz et al. 2017.[13]

Temperature and Climate Projections

What methods are used to record global surface temperatures and measure changes in climate?

Global surface temperatures are measured by using data from weather stations over land and by ships and buoys over the ocean. Global surface temperature records date back more than 300 years in some locations, and near-global coverage has existed since the late 1800s. Multiple research groups have examined U.S. and global temperature records in great detail, taking into account changes in instruments, the time of observations, station location, and any other potential sources of error. Although there are slight differences among datasets—due to choices in data selection, analysis, and averaging techniques—these differences do not change the clear result that global surface temperature is rising.

Climate change is best measured by assessing trends over long periods of time (generally greater than 30 years), which means we need global surface temperature records that include data from before the satellite age. Scientists who obtain, digitize, and collate long-term temperature records take great care to ensure that any potentially skewed measurements—such as a change in instrument method or location or a change in the time of day a recording is made—do not affect the integrity of the dataset. Researchers rigorously examine the data to identify and adjust for any such effects before using it to evaluate long-term climate trends. Different choices in data selection, analysis, and averaging techniques by multiple independent research teams mean that each dataset varies slightly. Even with these variations, however, multiple independently produced results are in very good agreement at both global and regional scales: all global surface temperature datasets indicate that the vast majority of Earth's surface has warmed since 1901 (Figure A5.8).

Scientists also consider other influences that could impact temperature records, such as whether data from thermometers located in cities are skewed by the urban heat island effect, where heat absorbed by buildings and asphalt makes cities warmer than the surrounding countryside. When determining climate trends, data corrections to these temperature records have adequately accounted for this effect. At the global scale, evidence of global warming over the past 50 years is still observed even if all of the urban stations are removed from the global temperature record. Studies have also shown that the warming trends of rural and urban areas that are in close proximity essentially match, even though the urban areas may have higher temperatures overall.[14]

Global Temperature Increase Shown in Multiple Datasets

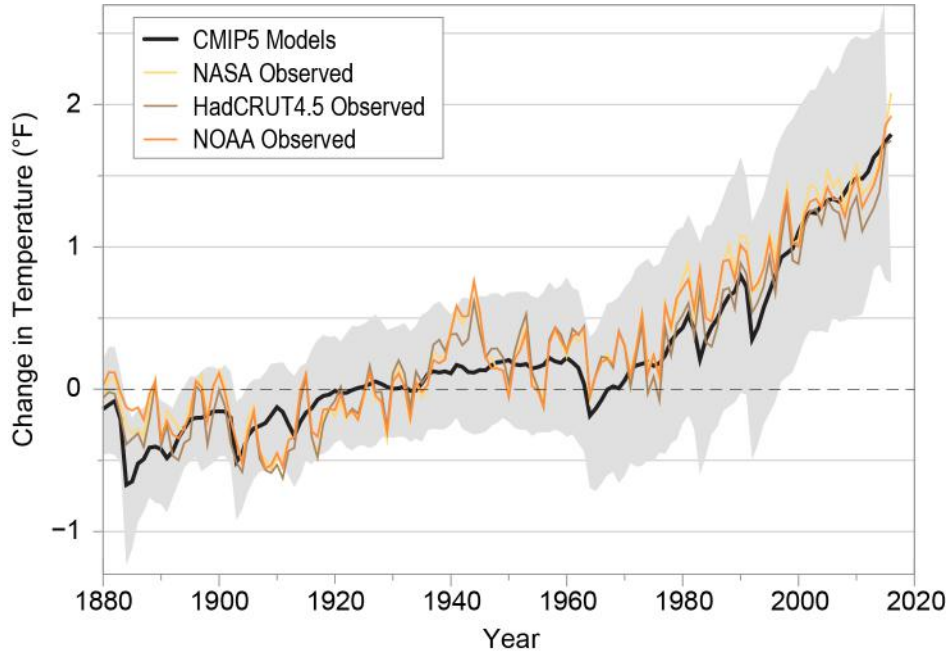

Figure A5.8: This chart shows observations of global annual average temperatures from three different datasets—one from NASA (yellow line), one from NOAA (orange line), and one from the University of East Anglia in conjunction with the United Kingdom's Met Office (HadCRUT4.5, brown line)—along with historical simulations of global temperature from the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble of climate models (black line). The lines show annual differences in temperature relative to the 1901–1960 average. Small differences among datasets, due to choices in data selection, analysis, and averaging techniques, do not affect the conclusion that global surface temperatures are increasing. Source: adapted from Knutson et al. 2016.[15]

Were there predictions of global cooling in the 1970s?

No. A review of the scientific literature from the 1970s shows that the broad climate science community did not predict "global cooling" or an "imminent" ice age. On the contrary, even then, discussions of human-related warming dominated scientific publications on climate and human influences.

Scientific understanding of what are called the Milankovitch cycles (cyclical changes in Earth's orbit that can explain the onset and ending of ice ages) led a few scientists in the 1970s to contemplate that the current warm interglacial period might be ending soon, leading to a new ice age over the next few centuries. These few speculations were picked up and amplified by the media. But at that time there were far more scientific articles describing how warming would occur from the increase in atmospheric concentrations of greenhouse gases from human activities, including the burning of fossil fuels (Figure A5.9). The latest information suggests that if Earth's climate was being controlled primarily by natural factors, the next cooling cycle would begin sometime in the next 1,500 years. However, humans have so altered the composition of the atmosphere that the next ice age has likely now been delayed. That delay could potentially be tens of thousands of years.[6]

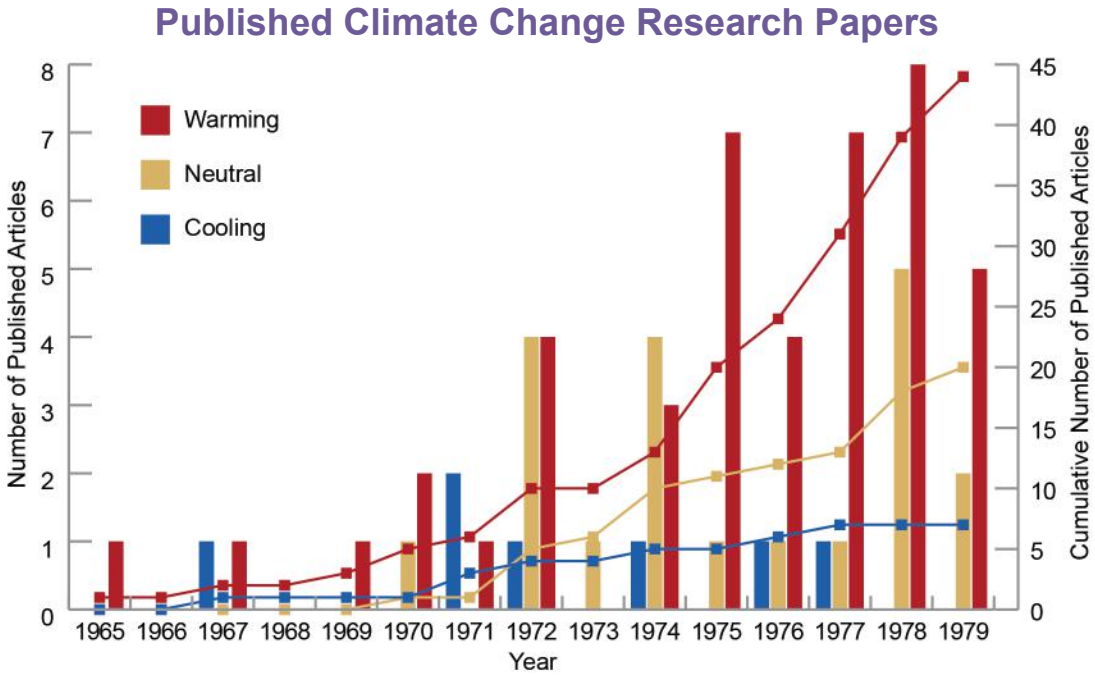

Figure A5.9: This chart compares the number of papers classified as predicting, implying, or providing supporting evidence for future global cooling, warming, and neutral categories published from 1965 to 1979. The bars indicate the number of articles published per year. The lines with squares indicate the cumulative number of articles published. Over this period the literature survey found 7 papers suggesting future cooling (blue line), 20 neutral (yellow line), and 44 warming (red line). Source: Peterson et al. 2008.[16]

How are temperature and precipitation patterns projected to change in the future?

Our world will continue to warm in the future because of historic emissions of greenhouse gases (GHGs), but the amount of warming will depend largely on the level of future emissions of GHGs and the choices humans make. If humans continue burning fossil fuels at or above our current rate through the end of the century, scientists project Earth will warm about 9°F, relative to preindustrial times (prior to 1750). Precipitation is projected to still be seasonally and regionally variable, but on average, projections show high-latitude areas getting wetter and subtropical areas getting drier. The frequency and intensity of very heavy precipitation are expected to increase, increasing the likelihood of flooding. Climate change will not affect all places in the same way or to the same degree but will vary at regional levels.

In the coming decades, scientists project that global average temperature will continue to increase (Ch. 2: Climate), although natural variability will continue to play a significant role in year-to-year changes. Sizeable variations from global average changes are possible at the regional level. Even if humans drastically reduce levels of GHG emissions, near-term warming will still occur because there is a lag in the temperature response to changes in atmospheric composition (Figure A5.10).

Over the next couple decades, natural variability and the response of Earth's climate system to historic emissions will be the primary determinants of observed warming. After about 2050, however, the rate and amount of emissions of GHGs released by human activities, as well as the response of Earth's climate system to those emissions, will be the primary determining factors in changes in global and regional temperature (Figure A5.13) (see also Ch. 2: Climate). Efforts to rapidly and significantly reduce emissions of GHGs can still limit the global temperature increase to 3.6°F (2°C) by the end of the century relative to preindustrial levels.[17]

Precipitation patterns are also expected to continue to change throughout this century and beyond. The trends observed in recent decades are expected to continue, with more precipitation projected to fall in the form of heavier precipitation events.[3] Such events increase the likelihood of flooding, even in drought-prone areas. As with increases in global average temperature, large-scale shifts towards wetter or drier conditions and the projected increases in heavy precipitation are expected to be greater under higher GHG emissions scenarios (for example, RCP8.5) versus lower ones (for example, RCP4.5). Projected warming is also expected to lead to an increase in the fraction of total precipitation falling as rain rather than snow, which reduces snowpack on the margins of areas that now have reliable snowpack accumulation during the cold season (see, for example, Ch. 24: Northwest, KM 2).

Observed and Projected Changes in Global Temperature

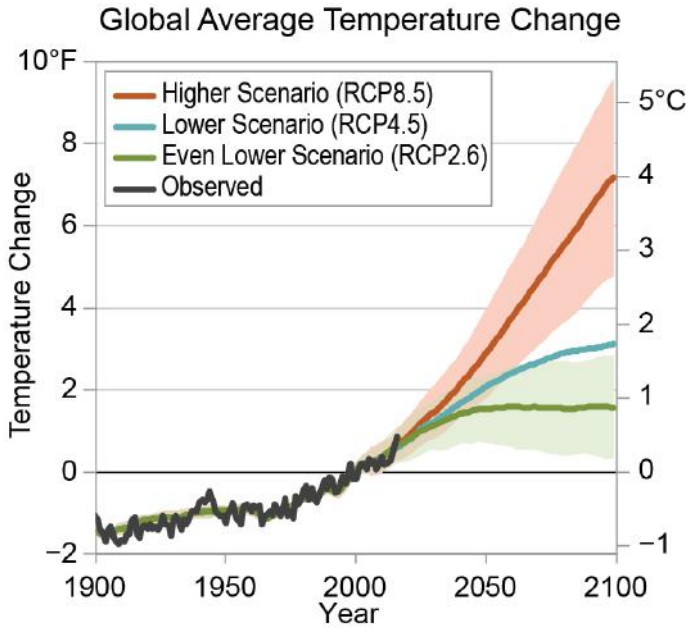

Figure A5.10: This figure shows both observed and projected changes in global average temperature. Under a representative concentration pathway (RCP) consistent with a higher scenario (RCP8.5; red) by 2080–2099, global average temperature is projected to increase by 4.2°–8.5°F (2.4°–4.7°C; burnt orange shaded area) relative to the 1986–2015 average. Under a lower scenario (RCP4.5; blue) global average temperature is projected to increase by 1.7°–4.4°F (0.9°–2.4°C; range not shown on graph) relative to 1986–2015. Under an even lower scenario (RCP2.6; green) temperature increases could be limited to 0.4°–2.7°F (0.2°–1.5°C; green shaded area) relative to 1986–2015. Limiting the rise in global average temperature to less than 2.2°F (1.2°C) relative to 1986–2015 is approximately equivalent to 3.6°F (2°C) or less relative to preindustrial temperatures. Thick lines within shaded areas represent the average of multiple climate models. The shaded regions illustrate the 5% to 95% confidence intervals for the respective projections. Source: adapted from Wuebbles et al. 2017.[4]

How do computers model Earth's climate?

Global climate models enable scientists to create "virtual Earths," where they can analyze causes and effects of past changes in temperature, precipitation, and other climate variables. Today's climate models can accurately reproduce broad features of past and present climate, such as the location and strength of the jet stream, the spatial distribution and seasonal cycle of precipitation, and the natural occurrence of extreme weather events, such as heat and cold waves, droughts and floods, and hurricanes. They also can reproduce historic natural cycles, such as the periodic occurrence of ice ages and interglacial warm periods, as well as the human-caused warming that has occurred over the last 50 years. While uncertainties remain, scientists have confidence in model projections of how climate is likely to change in the future in response to key variables, such as an increase in human-caused emissions of greenhouse gases, in part because of how accurately they can represent past climate changes.

Climate models are based on equations that represent fundamental laws of nature and the many processes that affect Earth's climate system. By dividing the atmosphere, land, and ocean into smaller spatial units to solve the equations, climate models capture the evolving patterns of atmospheric pressures, winds, temperatures, and precipitation. Over longer time frames, these models simulate wind patterns, high- and low-pressure systems, ocean currents, ice and snowpack accumulation and melting, soil moisture, extreme weather occurrences, and other environmental characteristics that make up the climate system (Figure A5.11).[18]

Some important processes, including cloud formation and atmospheric mixing, are represented by approximate relationships, either because the processes are not fully understood or they are at a scale that a model cannot directly represent. These approximations lead to uncertainties in model simulations of climate. Approximations are not the only uncertainties associated with climate models, as discussed in the FAQ "What are key uncertainties when projecting climate change?"

Comparison of Climate Models and Observed Temperature Change

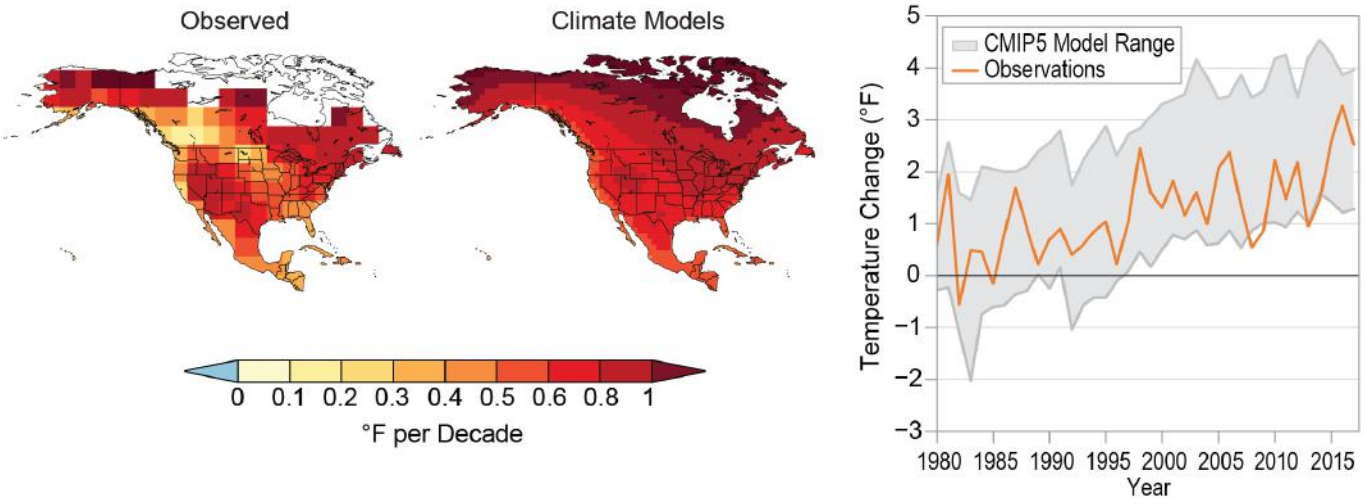

Figure A5.11: Climate simulations (right map) can capture the approximate geographical patterns and magnitude of the surface air temperature trend seen in observational data for the period 1980–2017 (left map). The warming pattern seen in the right map is an average based on 43 different global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5). The graphical representation shows the range of temperature changes simulated by the models for North America (relative to 1901–1960; gray shading, 5th to 95th percentile range) overlaid by the observed annual average temperatures over North America (orange line). The observed temperature changes are a result of both human contributions to recent warming and natural temperature variations. Averaging the simulations from multiple models suppresses the natural variations and thus shows mainly the human contribution, which is part of the reason small-scale details are different between the two maps. Sources: (maps) adapted from Walsh et al. 2014[6] (and graph) NOAA NCEI and CICS-NC.

Can scientists project the effects of climate change for local regions?

Yes, though there are limitations. With advances in computing power, the future effects of climate change can be projected more accurately for local communities. Local high-resolution (downscaled) climate modeling can be used to produce data at a scale of 1–20 miles. These downscaled projections show climate-related impacts at the local level and can be an important tool for community planners and decision-makers.

One significant research focus recently has been to develop models of climate impacts on a relatively small geographic scale. Most global climate projections use grid units that may be too coarse to properly represent mountains, coastlines, and other important features of a local landscape. Recently, two different approaches have been used by scientists to project local climate conditions.

The first is a statistical approach that uses local observations in conjunction with global models to project future changes. The local observations required for this approach are available only for limited regions and for a few climate variables (mainly temperature and precipitation; Figure A5.12).

The second method is a so-called dynamical approach that uses an additional high-resolution computer model—similar to a weather prediction model— to account for complex topography and varying land cover that can impact climate on the local level. High-resolution dynamical models are complete enough to simulate numerous climate variables (temperature, precipitation, winds, humidity, surface sunlight, etc.) and do not require the local observations required for the statistical approach. However, these models require an immense amount of computing power. Today's most powerful supercomputers enable climate scientists to examine the effects of climate change in ways that were impossible just five years ago. Over the next decade, computer speeds are predicted to increase 100-fold or more, improving climate projections and models on both the global and local levels.

It should also be noted that both statistical and dynamical approaches have biases and errors that, when combined with uncertainties from global model simulations, can reduce the level of confidence in these more localized projections (see Hayhoe et al. 2017[18] for more details).

Climate Modeling for Smaller Regions

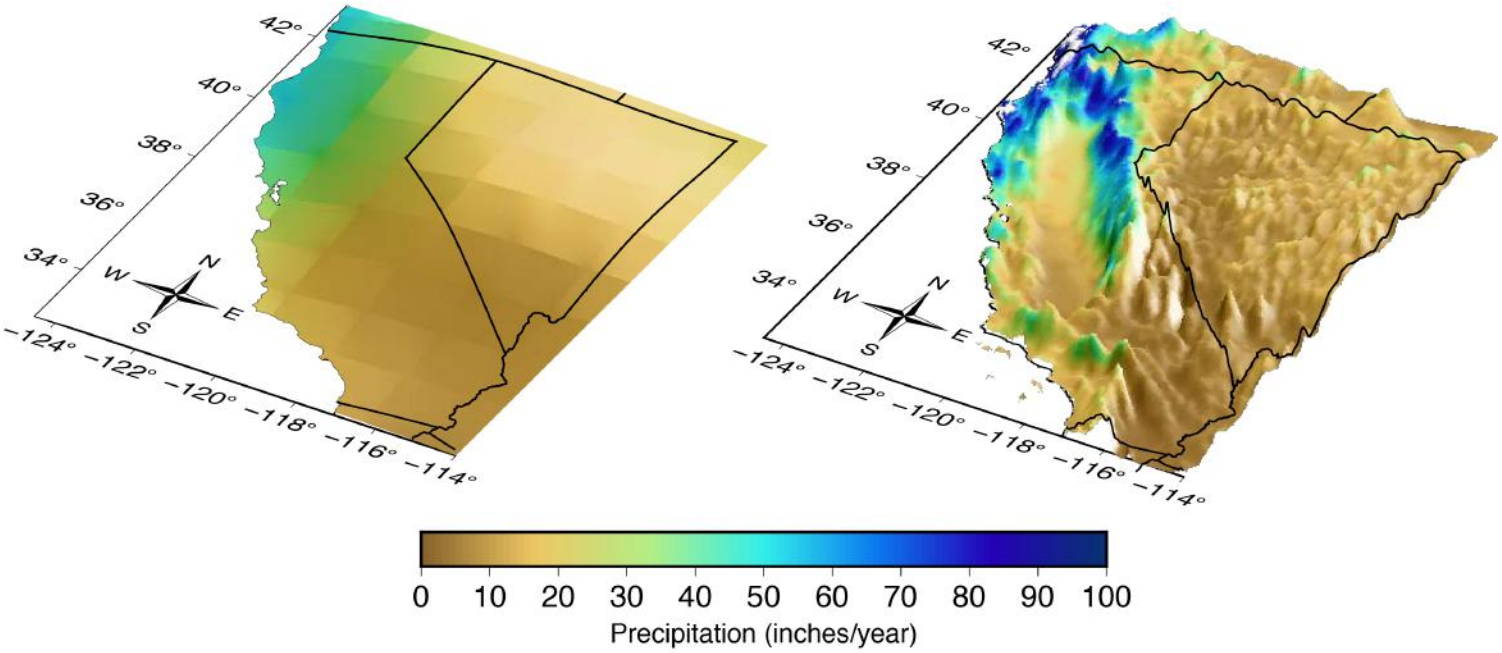

Figure A5.12: The figure shows projections of annual precipitation (in inches) in California and Nevada in a global climate model with a resolution of 100 miles (left) and, after using a statistical model to account for the effects of topography, at a resolution of 3.6-miles (right). The global model has only a few grid cells over the entire state of California, so it does not resolve the coastal mountain range, interior valley, or Sierra Nevada on the border with Nevada. The precipitation field in the right panel, by contrast, captures the wet conditions on the west slopes of the mountains and the dry, rain shadow region to the east of the mountains. The topography has been exaggerated for clarity and by the same amount in both panels. Source: UCSD Scripps Institute of Oceanography.

What are key uncertainties when projecting climate change?

The precise amount of future climate change that will occur over the rest of this century is uncertain, mainly due to uncertainties in emissions, natural variability, and differences in scientific models.

First, projections of future climate changes are usually based on scenarios (or sets of assumptions) regarding how future emissions may change due to changes in population, energy use, technology, and economics. Society may choose to reduce emissions or continue on a pathway of increasing emissions. The differences in projected future climate under different scenarios are generally small for the next few decades. By the second half of the century, however, human choices, as reflected in these scenarios, become the key determinant of future climate change (Figure A5.13).

A second source of uncertainty is natural variability, which affects the climate over timescales from months to decades. These natural variations are largely unpredictable, such as a volcanic eruption, and are superimposed on the warming from increasing greenhouse gases (GHGs).

A third source of uncertainty involves limitations in our current scientific knowledge. Climate models differ in the way they represent various processes (for example, cloud properties, ocean circulation, and aerosol effects). Additionally, climate sensitivity, or how much the climate will warm with a given increase in GHGs (often a doubling of GHG from preindustrial levels), is still a major source of uncertainty. As a result, different models produce small differences in projections of global average change. Scientists often use multiple models to account for the variability and represent this as a range of projected outcomes.

Finally, there is always the possibility that there are processes and feedbacks not yet being included in projections of climate in the future. For example, as the Arctic warms, carbon trapped in permafrost may be released into the atmosphere, increasing the initial warming due to human-caused emissions of GHGs, or an ice sheet may collapse, leading to faster than expected sea level rise.

However, for a given future scenario, the amount of future climate change can be specified within plausible bounds, with those bounds determined not only from the differences in how climate responds to a doubling of GHG concentrations among models but also by utilizing information about climate changes in the past (see Hayhoe et al. 2017[18] for more details).

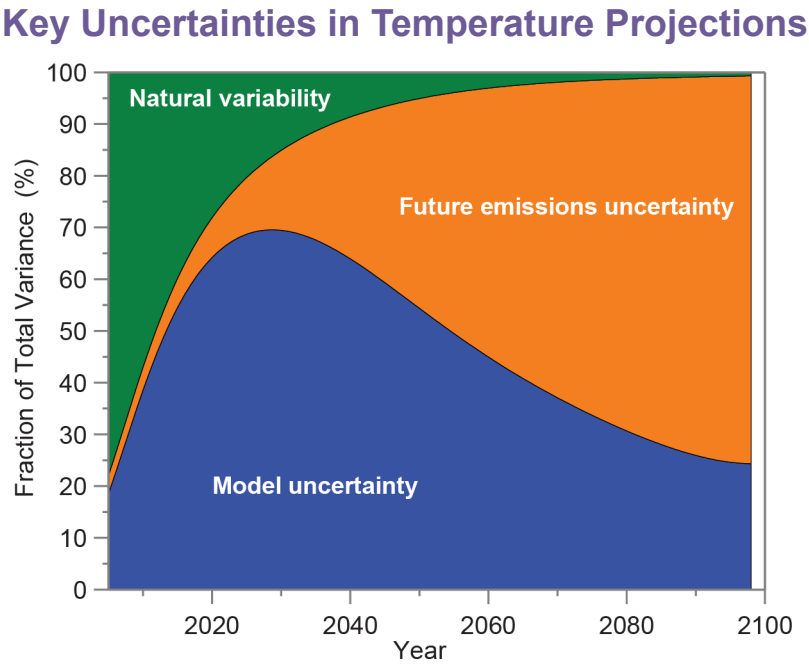

Figure A5.13: The graph shows the change in the fraction of total variance (uncertainty) of three components of total uncertainty in decadal average surface air temperature projections for the contiguous United States. Green represents natural variability, orange represents future emissions uncertainty, and blue represents model or scientific uncertainty (including in climate sensitivity). As the time period becomes more distant, the impact of natural variability becomes less significant due to the smaller variability over a larger period. Future emissions uncertainty increases as time progresses, since we are unable to determine the exact choices that will be made by humans in the future. The influence of model uncertainty on the total uncertainty of how climate will change decreases as the century progresses, due to advances in science and the creation of more accurate and precise assessment systems. This figure shows total uncertainty for the lower 48 states—as the size of the region is reduced, the relative importance of natural variability increases. It is important to note that this figure shows the fractional sources of uncertainty. The total amount of uncertainty increases through time. Source: adapted from Hawkins and Sutton 2009.[19] ©American Meteorological Society. Used with permission.

Is it getting warmer everywhere at the same rate?

Our world is warming overall, but temperatures are not increasing at the same rate everywhere. The average global temperature is projected to continue increasing throughout the remainder of this century due to greenhouse gas (GHG) emissions from human activities. Generally, high latitudes are expected to continue warming more than lower latitudes; coastal and island regions are expected to warm less than interior continent regions.

Temperature changes at a given location are a function of multiple factors, including global and local forces, and both human and natural influences. Though Earth's average temperature is rising, some locations could be cooling due to local factors. In some places, including the U.S. Southeast, temperatures do not show a warming trend over the last century as a whole, although they have been increasing since the 1960s (Ch. 19: Southeast). Possible causes of the observed lack of warming in the Southeast during the 20th century include increased cloud cover and precipitation, increases in the presence of fine particles (called aerosols) in the atmosphere, expanding forests, decreases in the amount of heat conducted from land due to increases in irrigation, and multidecadal variability in sea surface temperatures in both the North Atlantic and the tropical Pacific Oceans. At smaller geographic scales and time intervals, the relative influence of natural variations in climate compared to the human contribution is larger than at the global scale. A lack of warming or a decrease in temperature at an individual location does not negate the fact that, overall, the planet is warming.

Alaska, in contrast to the U.S. Southeast, has been warming twice as fast as the global average since the middle of the 20th century (Ch. 26: Alaska). Statewide average temperatures for 2014–2016 were notably warmer as compared to the last few decades, with 2016 being the warmest on record. Daily record high temperatures in the contiguous United States are now occurring twice as often as record low temperatures. In Alaska, starting in the 1990s, record high temperatures occurred three times as often as record lows, and in 2015, an astounding nine times as often (Ch. 26: Alaska).

Because Earth's climate system still has more energy entering than leaving, global warming has not yet equilibrated to the load of increased GHGs that have already accumulated in the atmosphere (for example, the oceans are still warming over many layers from surface to depth). Some GHGs have long lifetimes (for example, carbon dioxide can reside in the atmosphere for a century or more). Thus, even if the emissions of GHGs were to be sharply curtailed to bring them back to natural levels, it is estimated that Earth is committed to continued warming of more than 1°F by 2100.

At the global scale, some future years will be cooler than the preceding year; some decades could even be cooler than the preceding decade (Figure A5.14). Brief periods of faster temperature increases and also temporary decreases in global temperature can be expected to continue into the future as a result of natural variability and other factors. Nonetheless, each successive decade in the last 30 years has been the warmest in the period of reliable instrumental records (going back to 1850; Figure A5.15). In fact, the rate of warming has accelerated in the past several decades, and 17 of the 18 warmest years have occurred since 2001 (see FAQ "What do scientists mean by the

'warmest year on record'?"). Based on this historical record and assessed scenarios for the future, it is expected that future global temperatures, averaged over climate timescales of 30 years or more, will be higher than preceding periods as a result of emissions of CO_2 and other GHGs from human activities (Ch 2: Climate).

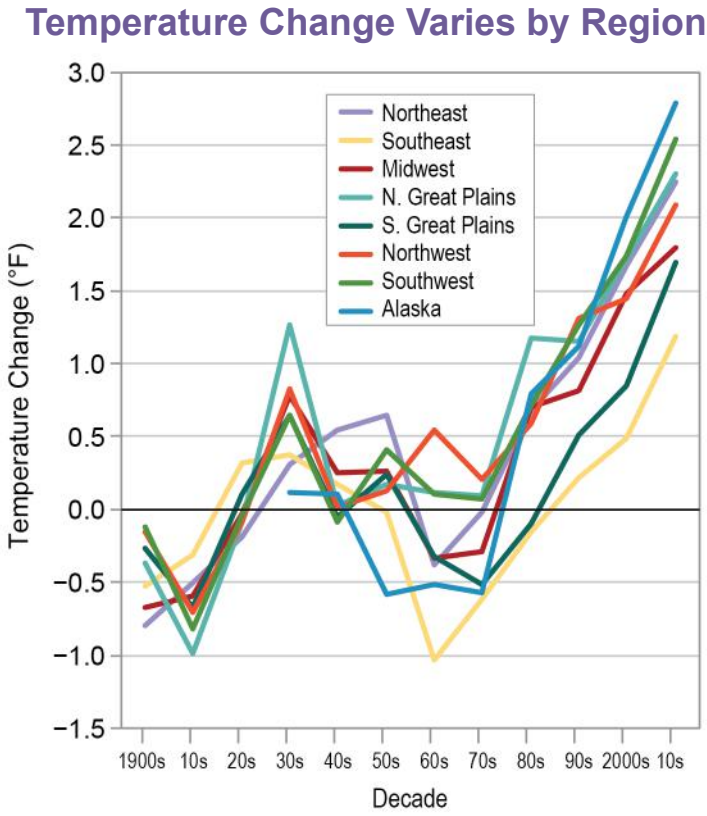

Figure A5.14: This graph shows changes in decadal-averaged temperature relative to the 1901–1960 average for eight of the ten NCA regions (see Front Matter, Figure 1). This figure shows how regional temperatures can be quite variable from decade to decade. All regions, however, have experienced warming over the last three decades or more. The most recent decade, the 2010s, refers to the 6-year period of 2001–2016. Source: adapted from Walsh et al. 2014.[6] Comparable data is not currently available for the Hawai'i and U.S-Affiliated Pacific Islands or U.S. Caribbean regions.

Average Global Temperature Is Increasing

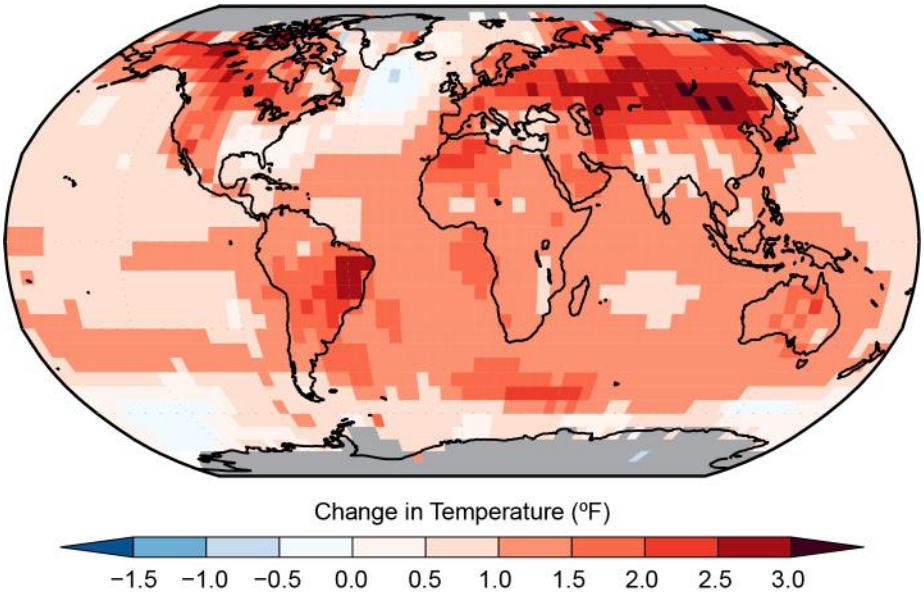

Figure A5.15: This map shows the observed changes in temperature for the 1986 to 2015 period relative to the 1901–1960 average. Shades of red indicate warming, while shades of blue indicate cooling. There are insufficient data in the Arctic Ocean and Antarctica for computing long-term changes. There are substantial regional variations in trends across the planet, though the overall trend is warming. Source: Vose et al. 2012.[20]

What do scientists mean by the "warmest year on record"?

When scientists declare it the "warmest year on record," they mean it's the warmest year since modern global surface temperature record keeping began in 1880. Global temperature data from NASA show that 2016 marked the sixth time this century that a new record high annual average temperature was set (along with 2002, 2005, 2010, 2014, and 2015) and that 17 of the 18 warmest years have occurred since 2001.

The "warmest year on record" means it is the warmest year in more than 130 years of modern record keeping of global surface temperature. Prior to 1880, observations did not cover a large enough area of Earth's surface to enable an accurate calculation of the global average temperature. To calculate the value in recent times, scientists evaluate data from roughly 6,300 stations around the world, on land, ships, and buoys.

The year the last National Climate Assessment was published, 2014, was the warmest year on record at the time, but it was surpassed by 2015, which was then surpassed by 2016. Data from NASA shows that 17 of the 18 warmest years have occurred since 2001, and the 6 warmest years on record have occurred this century (Figure A5.16). However, the global surface temperature is affected by natural variability in addition to climate change, so it is not expected that each year will set a new temperature record.

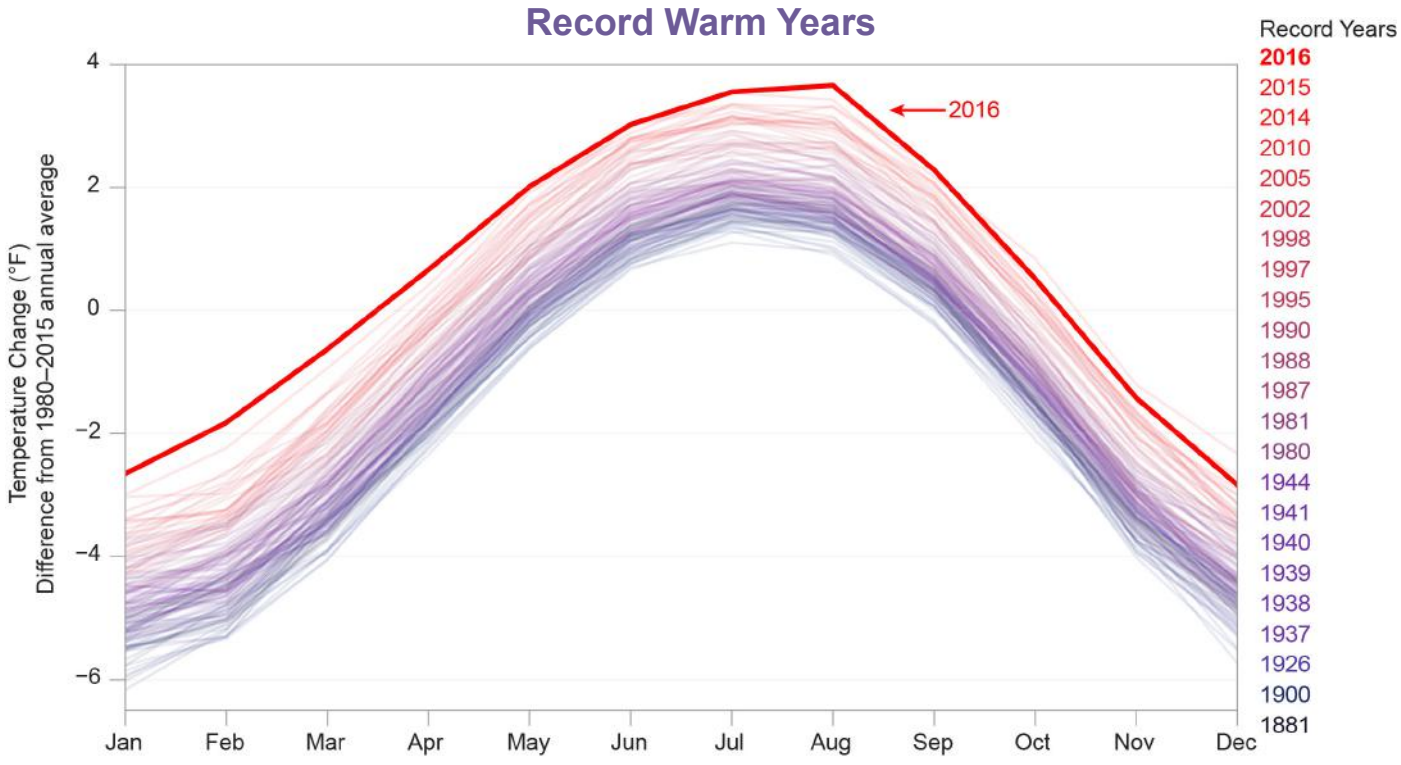

Figure A5.16: This graph shows global, monthly averaged temperature, relative to the 1980–2015 average, plotted over annual temperature cycles from 1880–2017. Record-breaking warm years are listed in the column to the right. The colored lines, shading from gray to blue to purple to red, indicate the years from 1880 to 2017, with 2016, bolded in red, being the hottest year on record. An animation of the complete time series is available online at https://nca2018.globalchange.gov/chapter/appendix-5/#fig-a5-16. Source: NASA.

How do climate projections differ from weather predictions?

The range of possible weather conditions at a specific location on any given day can vary considerably. The climate varies far less for that same location, because it is a measure of weather conditions averaged over 30 years or more. Because the range of possible climate conditions at a given location is much smaller than the range of possible weather conditions, scientists are able to project climate conditions decades into the future.

Projecting how climate may change decades in the future is a different scientific issue than forecasting weather a few days from now. Weather prediction means determining the exact location, time, and magnitude of specific events. Because the range of possible weather conditions can vary so widely, the weather forecast is extremely sensitive to even the smallest uncertainties or errors in our description of the state of the atmosphere at the start of a forecast. The impact of those uncertainties magnifies over time, which makes it very difficult to predict specific weather events at a given location more than a week or two into the future.

Because climate is the average weather at a given location over long periods of time (three decades or more), the range of possible climate conditions at a given location is much smaller than the range of possible weather conditions. For example, the daytime high temperature at a given location may vary by 30°F or more over the course of a day, while the annual average temperature over 30 years may vary by no more than a few degrees (Figure A5.17).

We can project how climate may change over time in response to natural forces, such as changes in incoming solar radiation, and in response to human activities, such as increasing the abundance of greenhouse gases (GHGs) or decreasing particle pollution. These projections are usually expressed in terms of probabilities describing a range of possible outcomes, not in the sort of exact (deterministic) language of many weather forecasts.

The difference between predicting weather and projecting climate is sometimes illustrated with a public health analogy. While it is impossible for us to determine the exact date and time when a particular individual will die, we can easily calculate the average age of death of all Americans for a time period in the past. In this case, weather is like the individual, while climate is like the average. To extend this analogy into the realm of climate change, we can also calculate the average life expectancy of Americans who smoke. We can predict that, on average, smokers will not live as long as nonsmokers. Similarly, we can project what the climate will be like if we emit lower levels of GHGs and what it will be like if we emit more.

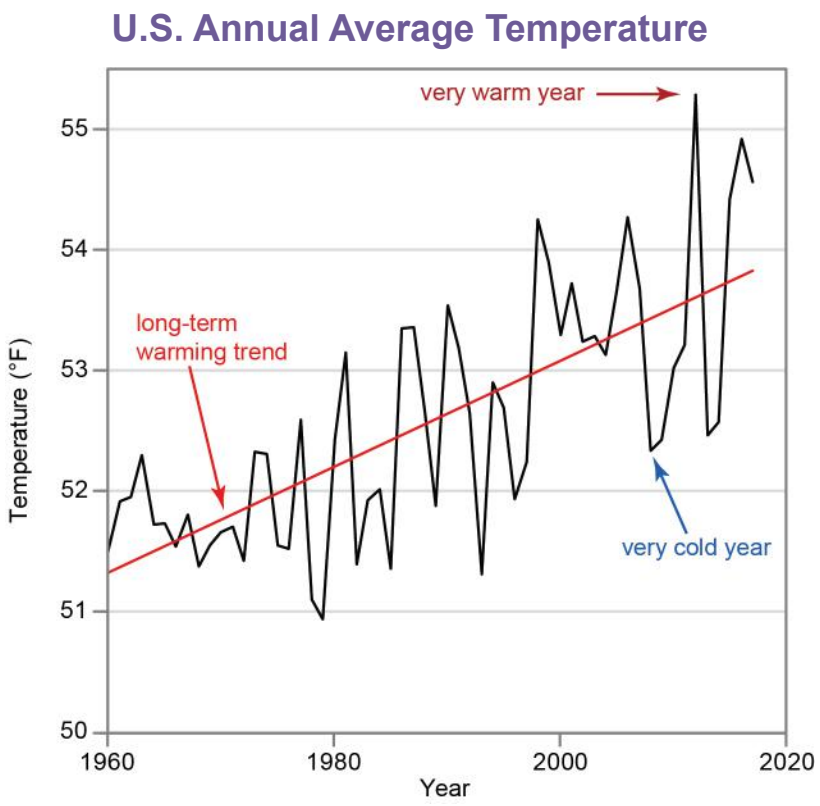

Figure A5.17: This figure shows the annual average surface temperature for the contiguous U.S. (black line) from 1960 to 2017, and the long-term warming trend (red line). Climate change refers to the changes in average weather conditions that persist for an extended period of time, over multiple decades or even longer. Year-to-year and even decade-to-decade, conditions do not necessarily tell us much about long-term changes in climate. One cold year, or even a few cold years in a row, does not contradict a long-term warming trend, just as one hot year does not prove it. Source: adapted from Walsh et al. 2014.[6]

Climate, Weather, and Extreme Events

Was there a "hiatus" in global warming?

Temperature records show that the long-term (30 years or longer) trend in increasing surface temperatures has not ceased. The rate of warming has been faster during some decades and slower during others, but these relatively short periods of time are not the basis for scientists' conclusion that sustained global warming is occurring.

"Global warming" refers to the increase in global average surface temperature that has been observed for more than a century. This warming is clearly revealed in both the surface temperature record and in satellite measurements of lower-atmospheric (troposphere) temperature. While the long-term trend shows warming, scientists expect that the rate of warming will vary from year to year or decade to decade due to the variability inherent in the climate system, or due to short-term changes in climate forcings, such as aerosols (dust, pollution, or volcanic particles) or incoming solar energy (Figure A5.18).

Temporary slowdowns in the rate of warming have occurred earlier in the historical record, even as carbon dioxide concentrations continued to rise. Temporary speedups have also occurred, most notably from the early 1900s to the 1940s and from the 1970s to the late 1990s. Computer simulations of both historical and future climate produce similar variations in the rate of warming, making recent variations in short-term temperature trends unsurprising.

From the mid-1940s to the mid-1970s, there was almost no increase in global temperature, possibly related to an increase in volcanic activity and/or human-caused aerosol emissions. Most notably, for the 15 years following the 1997–1998 El Niño event, the observed rate of temperature increase was smaller than what was projected by some climate models. However, during this period other indicators of climate change continued previous trends associated with warming, such as increasing ocean heat content and decreasing arctic sea ice extent (Figure A5.19; see Wuebbles et al. 2017,[4] Box 1.1).

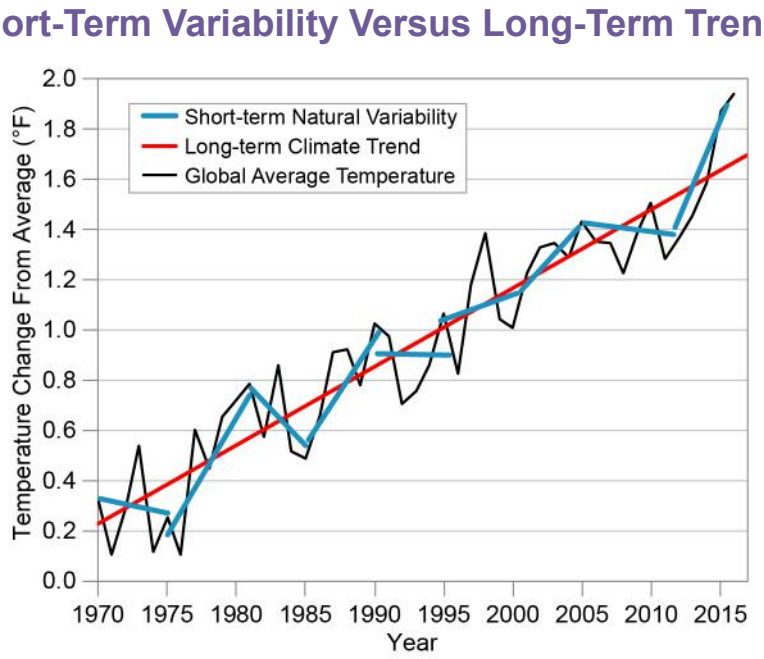

Figure A5.18: Short-term trends in global temperature (blue lines show approximate temperature trends at five-year intervals) can range from decreases to sharp increases. The evidence of climate change is based on long-term trends over 30 years or more (red line). The black line shows the annual average change in global surface temperature from 1970 to 2016 relative to 1901–1960. Source: adapted from Walsh et al. 2014.[6]

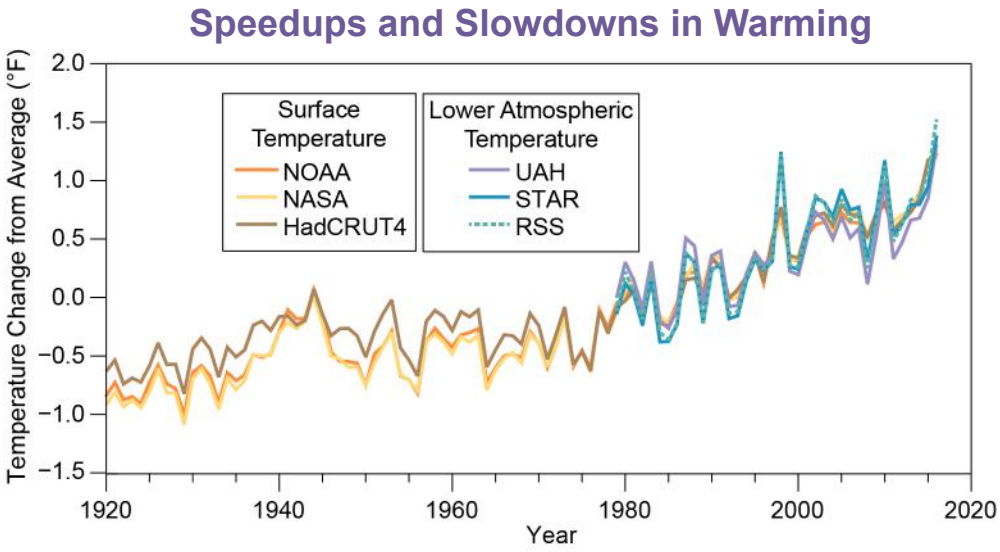

Figure A5.19: The figure shows global annual average surface temperatures (datasets are from NOAA [orange], NASA [yellow], and the United Kingdom's Met Office/University of East Anglia [HadCRUT4, brown]) and lower-atmospheric (tropospheric) temperatures (datasets are from University of Alabama–Huntsville [purple], NOAA [blue], and Remote Sensing Systems [blue dashed]) as compared to 1900–1960 averages. Decades of relatively faster or slower warming are observed within the long-term warming trend. Source: adapted from Trenberth 2015.[21]

What is an extreme event?

An extreme event is a weather or climate-related event that is particularly rare for a given time of year and location. These events include drought, wildfires, floods, severe storms (including hurricanes), heat waves, cold snaps, and heavy rains, and they can have devastating impacts on local communities, infrastructure, the economy, and the environment.

Scientists determine if an event is extreme or not by comparing measurements of weather and climate variables (rainfall, wind speed, temperature, etc.) with thresholds. Events above or below these thresholds are considered rare occurrences, such as events that rank in the highest or lowest 5% of observed values. Several thresholds may be used to define if a single event is considered extreme, and the threshold may change depending on the period of interest (day, month, season, year, etc.) and the chosen reference period (for example, 1961–1990 versus 1900–2000).

It is possible for a single event to meet the definition of an extreme event but not have a large impact. Conversely, it is possible for several types of events that may not be considered extreme individually to cause catastrophic impacts when taken together, such as a sequence of hot days that occur during dry conditions that worsen a drought, or several rainfall events occurring one after another that produce flooding (see Wuebbles et al. 2017, Knutson et al 2017, and Kossin et al. 2017 for more detail on extreme events[4,14,22]).

Have there been changes in extreme weather events?

Yes. Climate change can and has altered the frequency, intensity, duration, or timing of certain types of extreme weather events when compared to past time periods. The harmful effects of severe weather raise concerns about how climate change might alter the risk of such events.

While there have always been extreme events due to natural causes, the frequency and severity of some types of events have increased due to climate change (Figure A5.20) (see also Ch. 2: Climate). As average temperatures have warmed due to emissions of greenhouse gases (GHGs) from human activities, extreme high temperatures have become more frequent and extreme cold temperatures less frequent. From 2001 to 2012, more than twice as many daily high temperature records, as compared to low temperature records, were broken in the United States. With continued increases in the level of GHGs in the atmosphere, the chances for extreme high temperature will continue to increase, with the occurrence of extreme low temperatures becoming less common. Even with much warmer average temperatures later in the century, there may still be occasional record cold snaps, though occurrences of record heat will be more common.

Because warmer air can hold more moisture, heavy rainfall events have become more frequent and severe in some areas and are projected to increase in frequency and severity as the world continues to warm. Both the intensity and rainfall rates of Atlantic hurricanes are projected to increase (see, for example, Ch. 2: Climate, Box 2.5), with the strongest storms getting stronger in a warming climate. Recent research has shown how global warming can alter atmospheric circulation and weather patterns such as the jet stream, affecting the location, frequency, and duration of these and other extremes.[13]

More research would be required to improve scientific understanding of how human-caused climate change will affect other types of extreme weather events important to the United States, such as tornadoes and severe thunderstorms. These events occur over much smaller scales of time and space, which makes observations and modeling more challenging. Projecting the future influence of climate change on these events can also be complicated by the fact that some of the risk factors for these events may increase while others may decrease.[2,4,22]

Extreme Temperature and Precipitation Events

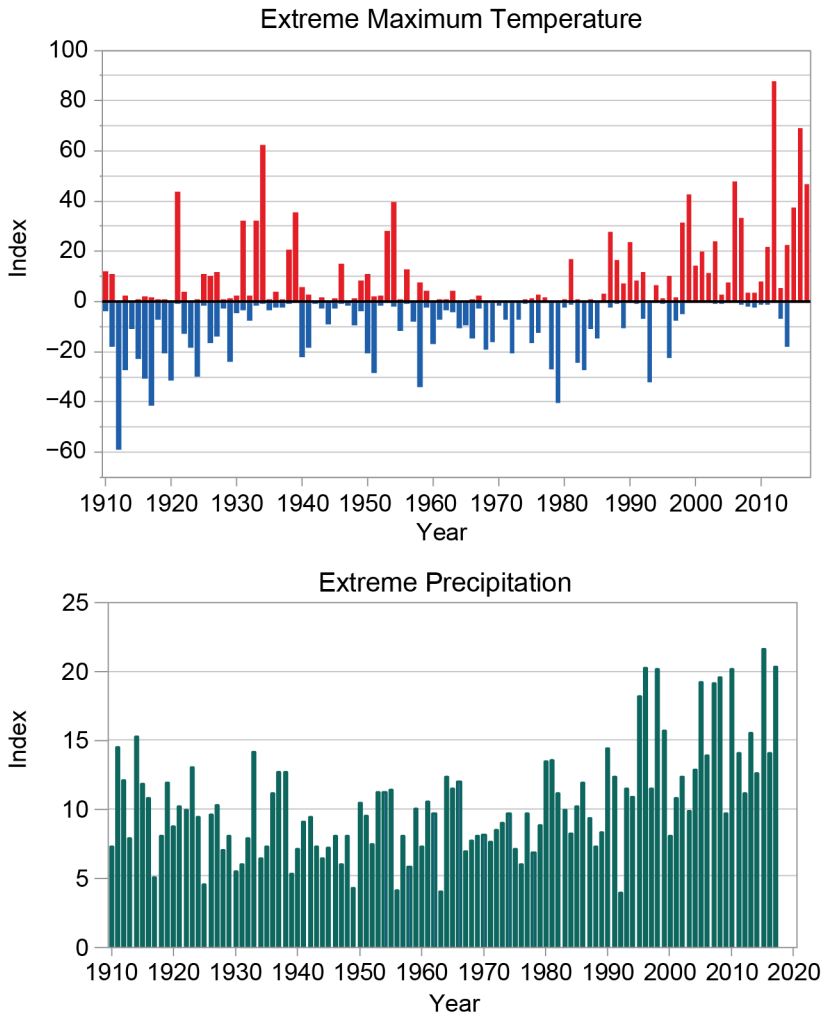

Figure A5.20: The top panel shows the percentage of land area in the contiguous United States that experienced maximum temperatures greatly above or below normal (upper or lower 10th percentile, respectively). The bottom panel shows the percentage of the land area for the contiguous United States that experienced extreme 1-day precipitation amounts that were greatly above normal. In the past 25 years, a much greater area of the country has experienced warmer extreme maximum temperatures and extreme rainfall. Sources: NOAA NCEI and CICS-NC.

Can specific weather or climate-related events be attributed to climate change?

While it is difficult to attribute a specific weather or climate-related event to any one cause, climate change can affect whether an event was more or less likely to occur. Climate change can also influence the severity of these events. Our ability to detect the influence of human-caused warming on particular kinds of extreme events depends both on the length and quality of our historical records of those events, as well as how well we can simulate the environmental processes that produce and sustain them.

Extreme event attribution is a relatively recent scientific advancement that seeks to determine whether climate change altered the likelihood of occurrence of a given extreme event.[14,23] A long-term, high-quality record of a given type of event and a computer model capable of producing a realistic simulation of the event are needed in order to assess the influence of climate change. Because of these data and modeling constraints, our ability to detect the influence of human-caused global warming on heat waves and, to a lesser extent, heavy rainfall events is better at present than our ability to detect its influence on tornadoes or hurricanes. As scientists collect more data and develop more advanced tools, they will be able to better quantify cause-and-effect relationships in the climate system, which should improve their ability to attribute how much human-caused climate change contributes to specific weather and climate-related events.

One example of event attribution comes from the recent California drought, where scientists found that human-caused climate change contributed 8%–27% to the severity of the drought.[24] Droughts are frequent in the Southwest and occur regardless of human activity, but human-caused climate change leads to increased evaporation and decreased soil moisture, intensifying droughts during periods of little rain.[14]

Could climate change make Atlantic hurricanes worse?

Atlantic hurricane activity has increased since the 1970s, but the relatively short length of high-quality hurricane records does not yet allow us to say how much of that increase is natural and how much may be due to human activity. With future warming, hurricane rainfall rates are likely to increase, as will the number of very intense hurricanes, according to both theory and numerical models. However, models disagree about whether the total number of Atlantic hurricanes will increase or decrease. Rising sea level will increase the threat of storm surge flooding during hurricanes.

Hurricane activity is undeniably linked to sea surface temperatures (see Ch. 2: Climate, Box 2.5 for a discussion on the 2017 Atlantic hurricane season). Other influences being equal, warmer waters yield stronger hurricanes with heavier rainfall. The tropical Atlantic Ocean has warmed over the past century, at least partly due to human-caused emissions of greenhouse gases. However, high-quality records of Atlantic hurricanes are too short to reliably separate any long-term trends in hurricane frequency, intensity, storm surge, or rainfall rates from natural variability.[22] This does not mean that no trends exist, only that the data record is not long enough to determine the cause.

Most models agree that climate change through the 21st century is likely to increase the average intensity and rainfall rates of hurricanes in the Atlantic and other basins. Models are less certain about whether the average number of storms per season will increase or decrease. Early modeling raised the possibility of a significant future increase in the number of Category 4 and 5 storms in the Atlantic (Figure A5.21). While that remains possible, the most recent high-resolution modeling provides mixed messages: some models project increases in the number of the basin's strongest storms, and others project decreases.[22]

Regardless of any human-influenced changes in storm frequency or intensity, rising sea level will increase the threat of storm surge flooding during hurricanes (Ch. 8: Coastal; Ch. 18: Northeast; Ch. 19: Southeast; Ch. 20: U.S. Caribbean; Ch. 23: S. Great Plains).

Category 4 and 5 Hurricane Formation: Now and in the Future

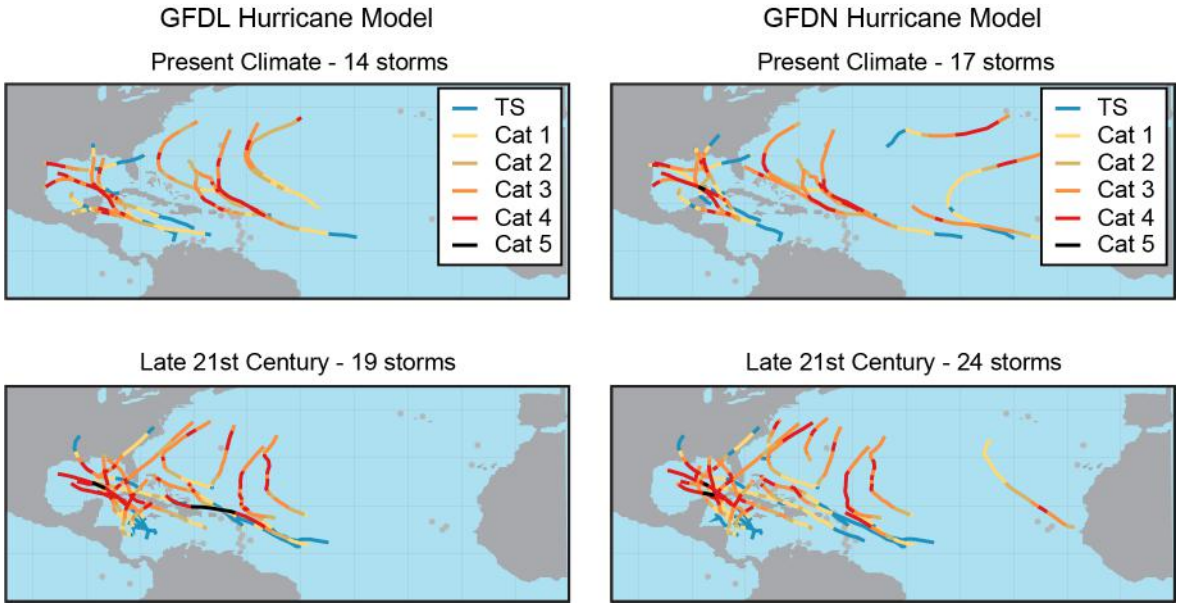

Figure A5.21: These maps show computer-simulated tracks and intensities of hurricanes reaching Categories 4 and 5 (intensity based on wind speeds ranging from TS for tropical storm strength up to Category 1 through Category 5 hurricanes). The top panels show hurricane tracks from two different models under current climate conditions (1980–2006). The bottom panels show projections from the same models but for late-21st century (2081–2100) conditions, both under the lower scenario (RCP4.5). These projections show an increase in the frequency of Category 4 and 5 hurricanes, with a higher tendency of these storms to shift towards the Gulf of Mexico, Florida, and the Caribbean (as opposed to remaining in the open Atlantic Ocean). Source: adapted from Knutson et al. 2013.[25] ©American Meteorological Society. Used with permission.

Societal Effects

How is climate change affecting society?

Climate change is altering the world around us in ways that become increasingly evident with each passing decade. Natural and human systems that we rely on are being impacted by more intense precipitation events, rising sea level, and a warming ocean and will be impacted by projected increases in the frequency of droughts and heat waves and other extreme weather patterns.

Many people are already being affected by the changes that are occurring, and more will be affected as these changes continue to unfold (Figure A5.22). In the Northeast and Northwest, fishing communities have to adapt to increasing ocean temperatures and acidification that impact fish and shellfish (Ch. 9: Oceans; Ch. 18: Northeast; Ch. 24: Northwest). Coastal communities, especially those located on islands, will need to confront rising sea levels, which are already contaminating freshwater supplies, flooding streets during high tides, and exacerbating storm surge flooding (Ch. 8: Coastal; Ch. 19: Southeast; Ch. 20: U.S. Caribbean; Ch. 27: Hawai'i and Pacific Islands). Shifts in the timing of the seasons and changes in the location of plants and animals affect communities dependent on those resources for tourism, economy, and/or cultural purposes (Ch. 7: Ecosystems; Ch. 15: Tribes; Ch. 26: Alaska).

Changes are not only happening in the oceans and along the coast. Farmers, the livestock they tend, and other outdoor laborers are expected to be adversely affected by warmer temperatures, an increasing frequency of heat waves, and an increasing number of warm nights (Ch. 10: Ag & Rural; Ch. 14: Human Health; Ch. 19: Southeast; Ch. 23: S. Great Plains). Some communities may have to adapt to both an increase in the frequency of drought and more rain falling as heavy precipitation, while deteriorating water infrastructure compounds those risks (Ch. 3: Water; Ch. 17: Complex Systems; Ch. 22: N. Great Plains; Ch. 25 Southwest). The geographic range and distribution of some pests and pathogens are projected to change in some regions, exposing livestock and crops to new or additional stressors and exposing more people to diseases transmitted by those pests (Ch. 14: Human Health; Ch. 21: Midwest).

Infrastructure across the country, which supports economic activity, is increasingly being tested and impacted by climate change, including airport runways affected by increased surface temperature and coastal streets inundated by high tide flooding (Ch. 12: Transportation). Much of the current built environment throughout the country has been developed based on the assumption that future climate will be similar to that of the past, which is no longer a valid assumption (Ch. 11: Urban). In general, the larger and faster the changes in climate, the more difficult it is for human and natural systems to adapt. Adaptation efforts not only help communities become more resilient, they may also create new jobs and help stimulate local economies (see FAQ "What are climate change mitigation, adaptation, and resilience?").

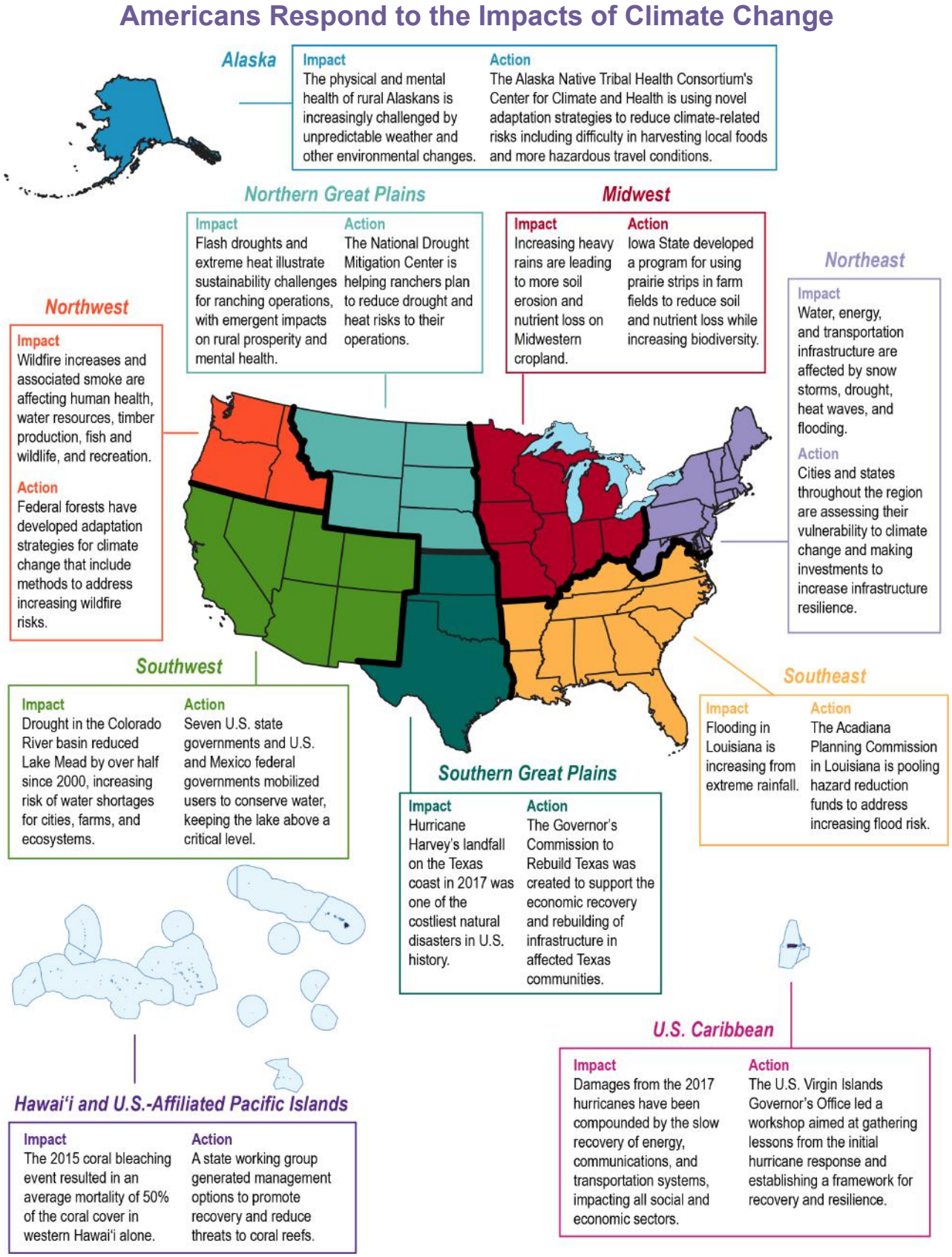

Figure A5.22: This map shows climate-related impacts that have occurred in each region since the Third National Climate Assessment in 2014 and response actions that are helping the region address related risks and costs. These examples are illustrative; they are not indicative of which impact is most significant in each region or which response action might be most effective. Source: NCA4 Regional Chapters.

What is the social cost of carbon?

The social cost of carbon is an estimate of the monetary value of the cumulative damages caused by long-term climate change due to an additional amount of carbon dioxide (CO_2) emitted. This value quantifies the potential benefits of a reduction in CO_2 emissions.

The social cost of carbon (SCC) includes the economic costs of climate change that will be felt in market sectors such as agriculture, energy services, and coastal resources, as well as nonmarket impacts on human health and ecosystems, to name a few.[26] SCC values are computed by simulating the "causal chain" from greenhouse gas emissions to physical climate change to climate damages in order to estimate the additional damages over time incurred from an additional metric ton of CO_2.[27] This value can be used to inform climate risk management decisions at national, state, and corporate levels, as well as in regulatory impact analysis to evaluate benefits of marginal CO_2 reductions—for example, in rules affecting appliance efficiency, power generation, industry, and transportation, such as the benefits of increased vehicle gas mileage standards. As with many complex, interacting systems, it is challenging to develop comprehensive SCC estimates, but this is an active area of research guided by recent recommendations from the National Academies of Sciences, Engineering, and Medicine to keep up with the current state of scientific knowledge, better characterize key uncertainties, and improve transparency.[28] Notably, estimating the SCC depends on normative social values such as time preference, risk aversion, and equity considerations that can lead to a range of values. Ongoing interdisciplinary collaborations and research findings from the climate change impacts, adaptation, and vulnerability literature—including those discussed in the Fourth National Climate Assessment—are being used to improve the robustness of climate damage quantification and, thus, SCC estimates.

What are climate change mitigation, adaptation, and resilience?

"Mitigation," "adaptation," and "resilience" are related but different terms in the context of climate change. Mitigation refers to actions that reduce the amount and speed of future climate change by reducing emissions of greenhouse gases (GHGs)or removing carbon dioxide from the atmosphere. Adaptation refers to adjustments in natural or human systems in response to a new or changing environment that exploit beneficial opportunities or moderate negative effects. Thus, adaptation is closely related to resilience, which is the capacity to prevent, withstand, respond to, and recover from a disruption with minimum damage to social well-being, the economy, and the environment.

Mitigation efforts can reduce emissions or increase storage of GHGs. For example, shifting from fossil fuels to low-carbon energy sources will generally result in the reduction of GHG emissions into the atmosphere. Mass transit, energy-efficient buildings, and electric vehicles can be used instead of high-emission alternatives. Land-use changes that increase the amount of carbon stored in soil and biomass, as well as some geoengineering techniques, constitute mitigation efforts that take carbon dioxide (CO_2) out of the atmosphere (see FAQ "Can geoengineering be used to remove carbon dioxide from the atmosphere or otherwise reverse global warming?") (see also Ch. 29: Mitigation).

Adaptation involves policies, strategies, and technologies designed to reduce the risk of harm from climate-related impacts. Some adaptation actions are technical engineering solutions designed to address specific impacts, such as building a seawall in the face of sea level rise or breeding new crops that do well in the context of drought. Other adaptation actions involve decision-making processes, policies, or approaches that bring people together to support coordinated action (Ch. 28: Adaptation). Adaptation often involves incremental adjustments to current systems, but larger transformations may be necessary, especially as some systems cross thresholds or tipping points.

Adaptation and mitigation actions can be undertaken simultaneously to reduce concentrations of GHGs in the atmosphere while also reducing the risk of climate-related impacts. Both adaptation and mitigation can have co-benefits—societal benefits that are not necessarily related to climate change (Ch. 29: Mitigation). For example, a new coastal restoration project to plant a mangrove forest will remove CO_2 from the atmosphere while providing valuable ecosystem services—a buffer against storm surges, reduced erosion, habitat for wildlife, and filtration of human pollutants (Ch. 8: Coastal).

Climate resilience refers to the capacity of a human or natural system to respond to and recover from climate-related hazards, such as droughts or floods, in ways that maintain their essential or valued identity, functions, and structure. Resilient systems respond to climate stressors or impacts with less harm while also improving their ability to absorb future impacts and maintaining capacity for adaptation and learning. A resilient rural community might have the capacity to share knowledge and resources to help farmers deal with droughts while improving their ability to absorb future impacts by building long-term structures to conserve water resources (Ch. 24: Northwest). Resilience can be bolstered by diversity (such as species diversity or employment diversity), redundancy (the ability for one part of the system to take over essential functions if another is damaged), social networks, knowledge sharing, and good governance (Ch. 7: Ecosystems).

Is timing important for climate mitigation?

Yes. The choices made today largely determine what impacts may occur in the future. Carbon dioxide can persist in the atmosphere for a century or more, so emissions released now will still be affecting climate for years to come. The sooner greenhouse gas (GHGs) emissions are reduced, the easier it may be to limit the long-term costs and damages due to climate change. Waiting to begin reducing emissions is likely to increase the damages from climate-related extreme events (such as heat waves, droughts, wildfires, flash floods, and stronger storm surges due to higher sea levels and more powerful hurricanes).

The effect of increasing atmospheric concentrations of carbon dioxide (CO_2) and other GHGs on the climate system can take decades to be fully realized. The resulting change in climate and the impacts of those changes can then persist for centuries. The longer these changes in climate continue, the greater the resulting impacts; some systems may not be able to adapt if the change is too much or too fast.

The long-term equilibrium temperature from GHG emissions will be a function of cumulative emissions over time, not the specific year-to-year emissions. Thus, staying within a specific warming target will depend on the total net emissions (including increases in carbon uptake) over a given future period.

However, the timing and nature of changes are important in both reducing short-term warming and meeting any particular long-term warming limit. Long-term reductions in the rate and magnitude of global warming can be made by reducing total emissions of CO_2. Near-term reductions in the rate of climate change can be made by reducing human-caused emissions of short-lived but highly potent GHGs such as methane and hydrofluorocarbons. These pollutants remain in the atmosphere from weeks to about a decade—much shorter than CO_2—but have a much greater warming influence than CO_2 (Figure A5.23).[17]

Benefit of Earlier Action to Reduce Emissions

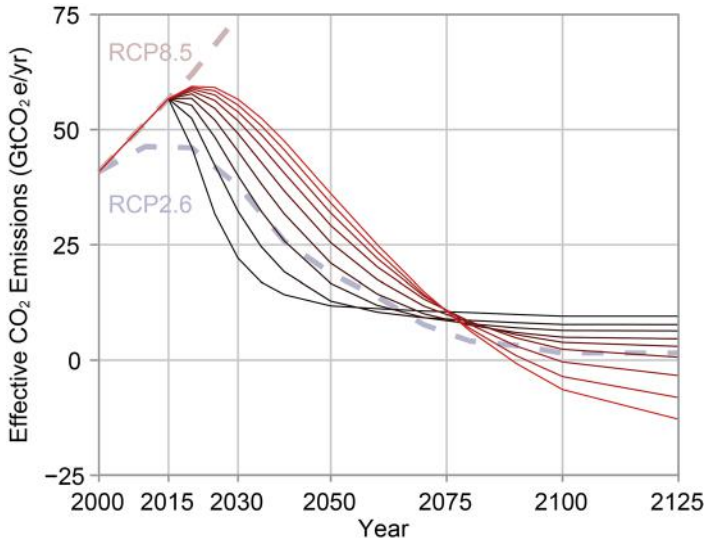

Figure A5.23: This figure shows possible future pathways for global annual emissions of GHGs for which the global mean temperature would likely (66%) not exceed 3.6°F (2°C) above the preindustrial average. The black curves on the bottom show the fastest reduction in emissions, with rapid near-term mitigation and little to no negative emissions required in the future. The red curves on top show slower rates of mitigation, with slow near-term reductions in emissions and large negative emission requirements in the future. Here, the annual global GHG emissions are in units of gigatons of CO_2 equivalent, a measurement that expresses the warming impact of all GHGs in terms of the equivalent amount of CO_2. Source: adapted from Sanderson et al. 2016.[29]

Are there benefits to climate change?

While some climate changes currently have beneficial effects for specific sectors or regions, many studies have concluded that climate change will generally bring more negative effects than positive ones in the future. For example, current benefits of warming include longer growing seasons for agriculture, more carbon dioxide for plants, and longer ice-free periods for shipping on the Great Lakes. However, longer growing seasons, along with higher temperatures and increased carbon dioxide levels, can increase pollen production, intensifying and lengthening the allergy season. Longer ice-free periods on the Great Lakes can result in more lake-effect snowfalls.

Many analyses of this question have concluded that climate change will, on balance, bring more negative effects than positive ones in the future. This is largely because our society and infrastructure have been built for the climate of the past, and changes from those historical climate conditions impose costs and management challenges (Ch. 11: Urban). For example, while longer warm seasons may provide a temporary economic boon to coastal communities reliant on tourism, many of these same areas are vulnerable not only to sea level rise but also to risks from ocean acidification and warmer waters that can impact the ecosystems (such as coral reefs) that bring people to the coasts (Ch. 8: Coastal). As another example, while some studies have shown that certain crops in certain regions may benefit from additional carbon dioxide (CO_2) in the atmosphere (sometimes referred to as the CO_2 fertilization effect), these potential gains are expected to be offset by crop stress caused by higher temperatures, worsening air quality, and strained water availability (see FAQ "How do higher carbon dioxide concentrations affect plant communities and crops?") (see also Ch. 10: Ag & Rural). Furthermore, any accrued benefits are likely to be short-lived and depreciate significantly as warming continues through the century and beyond.

Are some people more vulnerable to climate change than others?

Yes. Climate change affects certain people and populations differently than others. Some communities have higher exposure and sensitivity to climate-related hazards than others. Some communities have more resources to prepare for and respond to rapid change than others. Communities that have fewer resources, are underrepresented in government, live in or near deteriorating infrastructure (such as damaged levees), or lack financial safety nets are all more vulnerable to the impacts of climate change.

Vulnerability here refers to the degree to which physical, biological, and socioeconomic systems are susceptible to and unable to cope with adverse impacts of climate change. Vulnerability encompasses sensitivity, adaptive capacity, exposure, and potential impacts. For example, older people living in cities with no air conditioning have less adaptive capacity and increased sensitivity and vulnerability to heat stress during extreme heat events (Ch. 14: Human Health). Communities that live on atolls in the Marshall Islands have high exposure and are acutely at risk to sea level rise and saltwater intrusion due to the low land height and small land area (Ch. 27: Hawai'i & Pacific Islands). A history of neglect, political or otherwise, in a given neighborhood can result in dilapidated infrastructure, which in turn can lead to situations such as levee failures, making whole communities vulnerable to flooding and other potential impacts (Ch. 14: Human Health). Poverty can make evacuation during storm events challenging and can make rebuilding or relocating harder following an extreme event. In some Indigenous communities, lack of water and sanitation systems can put people at risk during drought (Ch. 15: Tribes). Additionally, some subpopulations are already more affected by environmental exposures, such as air pollution or extreme heat. If communities or individuals experience a combination of these vulnerability factors, they are at even greater risk. Vulnerable communities and individuals face these disparities today and will likely face increased challenges in the future under a changing climate.

How will climate change impact economic productivity?

Many impacts of climate change are expected to have negative effects on economic productivity, such as increased prices of goods and services. For example, increased exposure to extreme heat may reduce the hours some individuals are able to work. Physical capital—such as food, equipment, and property—that is derived from the production of goods and services may be impacted because of lower production and higher costs as a result of climate change. Sea level rise, stronger storm surges, and increased heavy downpours that cause flooding can disrupt supply chains or damage properties, structures, and infrastructure that form the backbone of the Nation's economy.

High temperatures and storm intensity, which are both linked to more deaths and illness, are projected to increase due to climate change, which would in turn increase health care costs for medical treatment. At the same time, these health effects directly impact labor markets. Workers in industries with the greatest exposure to weather extremes may decrease the amount of time they spend at work, while workers across a wide range of sectors may find their productivity impaired while on the job (Ch. 14: Human Health). These labor market impacts translate into lower earnings for workers and firms.[30,31]

Climate change is likely to affect physical capital that serves as an important input to economic production. In farming, where weather is a key determinant of agricultural yield, increasing temperatures and drought may lead to net decreases in the amount of food that farms produce (Ch.10: Ag & Rural).[32] Extreme heat can also cause manufacturing equipment to break down with greater frequency, while rising sea levels and increased storm intensity can destroy equipment and property across all types of economic activities along American coastlines.[30,33]

In addition to damaging private property, increased weather extremes can destroy vital public infrastructure, such as roads, bridges, and ports. Since this infrastructure is an integral part of supply chains that drive the American economy, a disruption in their accessibility—or even their destruction—can have large impacts on corporate profits, while their repairs require a diversion of resources away from other useful government projects or an increase in taxes to finance reconstruction (Ch. 11: Urban).[34,35]

Can we slow climate change?

Yes. While we cannot stop climate change overnight, or even over the next several decades, we can limit the amount of climate change by reducing human-caused emissions of greenhouse gases (GHGs). Even if all human-related emissions of carbon dioxide and other GHGs were to stop today, Earth's temperature would continue to rise for a number of decades and then slowly begin to decline. Ultimately, warming could be reversed by reducing the amount of GHGs in the atmosphere. The challenge in slowing or reversing climate change is finding a way to make these changes on a global scale that is technically, economically, socially, and politically viable.

The most direct way to significantly reduce the magnitude of future climate change is to reduce the global emissions of GHGs. Emissions can be reduced in many ways, and increasing the efficiency of energy use is an important component of many potential strategies (Ch. 29: Mitigation). For example, because the transportation sector accounts for about 29% of the energy used in the United States, developing and driving more efficient vehicles and changing to fuels that do not contribute significantly to GHG emissions over their lifetimes would result in fewer emissions per mile driven. A large amount of energy in the United States is also used to heat and cool buildings, so changes in building design could dramatically reduce energy use (Ch 29: Mitigation). While there is no single approach that will solve all the challenges posed by climate change, there are many options that can reduce emissions and help prevent some of the potentially serious impacts of climate change (Figure A5.24).[17]

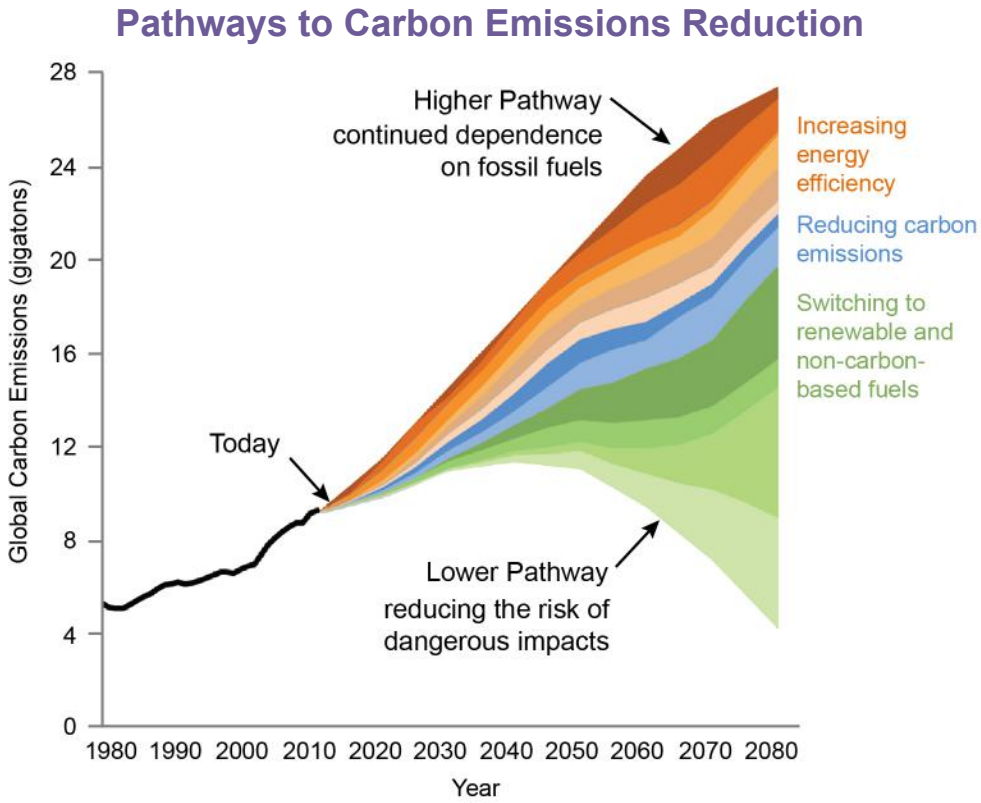

Figure A5.24: Reducing carbon emissions from a higher scenario (RCP8.5) to a lower scenario (RCP4.5) can be accomplished with a combination of many technologies and policies. In this example, these emissions reduction "wedges" could include increasing the energy efficiency of appliances, vehicles, buildings, electronics, and electricity generation (orange wedges); reducing carbon emissions from fossil fuels by switching to lower-carbon fuels or capturing and storing carbon (blue wedges); and switching to renewable and non-carbon-emitting sources of energy, including solar, wind, wave, biomass, tidal, and geothermal (green wedges). The shapes and sizes of the wedges shown here are illustrative only. Source: adapted from Walsh et al. 2014.[6]

Can geoengineering be used to remove carbon dioxide from the atmosphere or otherwise reverse global warming?

In theory, it may be possible to reverse some aspects of global warming through technological interventions called geoengineering, which can complement mitigation and adaptation. But many questions remain. Geoengineering approaches generally fall under two categories: 1) carbon dioxide removal and 2) reducing the amount of the sun's energy that reaches Earth's surface. Due to uncertain costs and risks of some geoengineering approaches, more traditional mitigation actions to reduce emissions of greenhouse gases (GHGs) are generally viewed as more feasible for avoiding the worst impacts from climate change currently. However, targeted studies to determine the feasibility, costs, risks, and benefits of various geoengineering techniques could help clarify the impacts.

Removal of carbon dioxide (CO_2) from the atmosphere could be undertaken by applying land management methods that increase carbon storage in forests, soils, wetlands, and other terrestrial or aquatic carbon reservoirs. Trees and plants draw down CO_2 from the atmosphere during photosynthesis and store it in plant structures. Reforesting large tracts of deforested lands would help reduce atmospheric concentrations of CO_2. New technologies could also be used to capture CO_2 either directly from the atmosphere or at the point where it is produced (such as at coal-fired power plants) and store it underground. However, CO_2 removal may be costly and has long implementation times, and the removal of CO_2 from the atmosphere must be essentially permanent if climate impacts are to be avoided.[17,36]

Solar radiation management (SRM) is an intentional effort to reduce the amount of sunlight that reaches Earth's surface by increasing the amount of sunlight reflected back to space. Since SRM does not reverse the increased concentrations of CO_2 and other GHGs in the atmosphere, this approach does not address direct impacts from elevated CO_2, such as damage to marine ecosystems from increasing ocean acidification.[17,37] Instead, it introduces another human influence on the climate system that partially cancels some of the effects of increased GHGs in the atmosphere. SRM methods include making clouds brighter and more reflective, injecting reflective aerosol particles into the upper or lower atmosphere, or increasing the reflectivity of Earth's surface. SRM can work in conjunction with CO_2 removal and other mitigation efforts and can be phased out over time. Yet this method would require sustained costs, has not been well studied, and could have harmful unintended consequences, such as stratospheric ozone depletion.[38]

Ecological Effects

What causes global sea level rise, and how will it affect coastal areas in the coming century?

Global sea level is rising, primarily in response to two factors: 1) thermal expansion of ocean waters and 2) melting of land-based ice, both due to climate change. Thermal expansion refers to the physical expansion (or increase in volume) of water as it warms. Melting of mountain glaciers and the Antarctic and Greenland ice sheets contributes additional water to the oceans, thereby raising global average sea level. Global average sea level has risen 7–8 inches since 1880, and about 3 inches of that has occurred since 1993. Sea level rise will increasingly contribute to high tide flooding and intensify coastal erosion over the coming century.

At any given location, the situation is more complicated because other factors come into play. For example, coastlands are rising in some places and sinking in others due to both natural causes (such as tectonic shifts) and human activities (such as groundwater or hydrocarbon extraction). Where coastlands are rising as fast as (or faster than) sea level, relative local sea level may be unchanged (or decreasing). Where coastlands are sinking (called subsidence), relative local sea level may be rising faster than the global average (Figure A5.25) (see also Ch. 23: S. Great Plains). Other variables can influence relative sea level locally, including natural climate variability patterns (for example, El Niño/La Niña events) and regional shifts in wind and ocean current patterns.[39]

Global sea level rise is already affecting the U.S. coast in many locations (Ch. 8: Coastal). High tide flooding with little or no storm effects (also referred to as nuisance, sunny-day, or recurrent flooding), coastal erosion, and beach and wetland loss are all increasingly common due to decades of local relative sea level rise (Ch. 19: Southeast).[39] Sea level is expected to continue rising at an accelerating rate this century under either a lower or higher scenario (RCP4.5 or RCP8.5), increasing the frequency of high tide flooding, intensifying coastal erosion and beach and wetland loss, and causing greater damage to coastal properties and structures due to stronger storm surges (Ch. 18: Northeast; Ch. 8: Coastal). Relative local sea level rise projections can be visualized at https://coast.noaa.gov/digitalcoast/tools/slr.html.

Relative Sea Level Projected to Rise Along Most U.S. Coasts

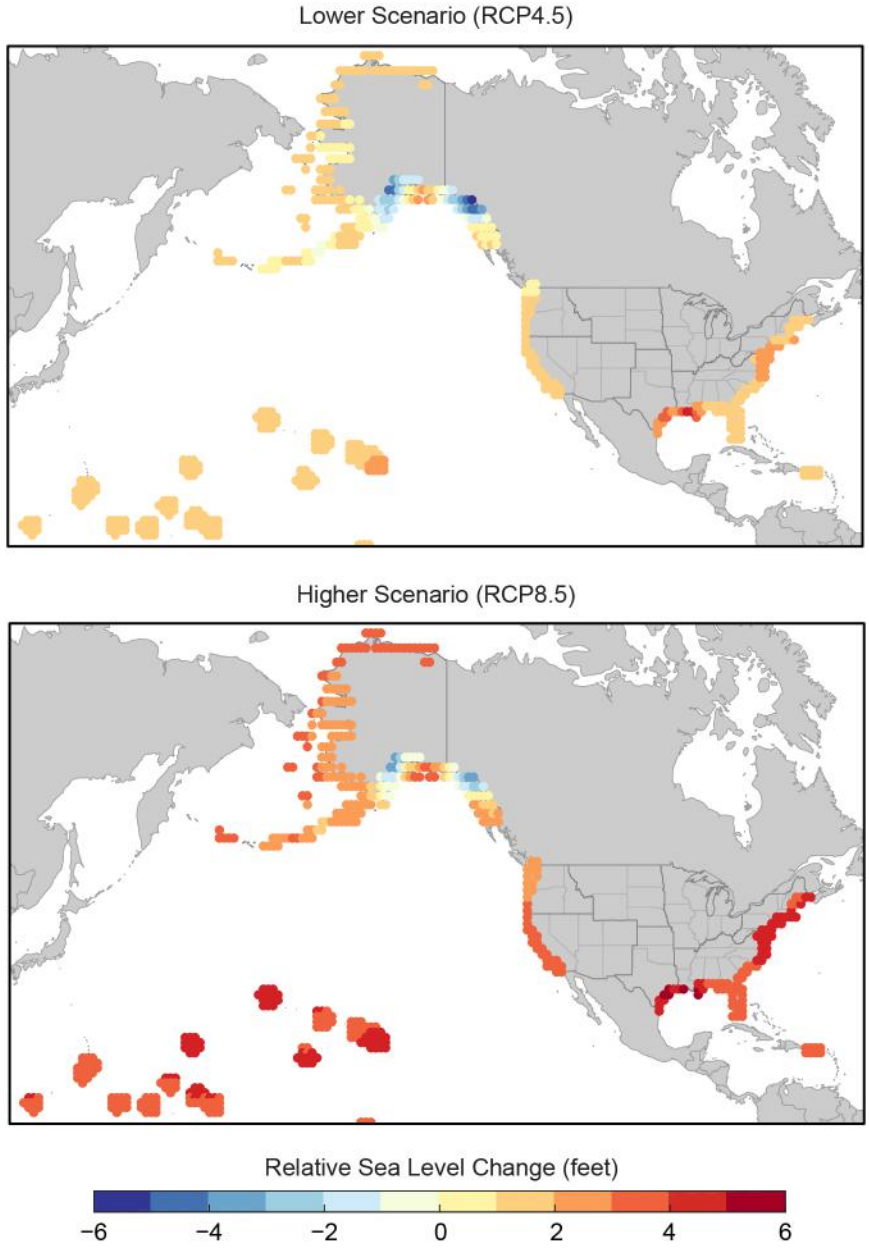

Figure A5.25: The maps show projections of change in relative sea level along the U.S. coast by 2100 (as compared to 2000) under the lower and higher scenarios (RCP4.5 and RCP8.5, top and bottom panels, respectively).[39] Globally, sea levels will continue to rise from thermal expansion of the ocean and melting of land-based ice masses (such as Greenland, Antarctica, and mountain glaciers). Regionally, however, the amount of sea level rise will not be the same everywhere. Where land is sinking (as along the Gulf of Mexico coastline), relative sea level rise will be higher, and where land is rising (as in parts of Alaska), relative sea level rise will be lower. Changes in ocean circulation (such as the Gulf Stream) and gravity effects due to land ice melt will also alter the heights of the ocean regionally. Sea levels are expected to continue to rise along almost all U.S. coastlines, and by 2100, under the higher scenario, coastal flood heights that today cause major damages to infrastructure would become common during high tides nationwide. Source: adapted from Sweet et al. 2017.[40]

How does global warming affect arctic sea ice cover?

The Arctic region has warmed by about 3.6°F since 1900—double the rate of the global temperature increase. Consequently, sea ice cover has declined significantly over the last four decades. In the summer and fall, sea ice area has dropped by 40% and sea ice volume has dropped 70% relative to the 1970s and earlier. Decline in sea ice cover plays an important role in arctic ecosystems, ultimately impacting Alaska residents.

Arctic sea ice today is in the most reduced state since satellite measurements began in the late 1970s, and the current rate of sea ice loss is also unprecedented in the observational record (Figures A5.26 and A5.27) (see also Ch. 2: Climate). Arctic sea ice cover is sensitive to climate change because strong self-reinforcing cycles (positive feedbacks) are at play. As sea ice melts, more open ocean is exposed. Open ocean (a dark surface) absorbs much more sunlight than sea ice (a reflective white surface). That extra absorbed sunlight leads to more warming locally, which in turn melts more sea ice, creating a positive feedback (Ch. 2: Climate). Annual average arctic sea ice extent has decreased between 3.5% and 4.1% per decade since the early 1980s, has become thinner by 4.3 to 7.5 feet, and has started melting earlier in the year. September sea ice extent, when the arctic sea ice is at a minimum, has decreased by 10.7% to 15.9% per decade since the 1980s. Scientists project sea ice-free summers in the Arctic by the 2040s (Figure A5.27) (see Ch. 26: Alaska).[2]

Arctic sea ice plays a vital role in arctic ecosystems. Changes in the extent, duration, and thickness of sea ice, along with increasing ocean temperature and ocean acidity, alter the distribution of Alaska fisheries and the location of polar bears and walruses, all of which are important resources for Alaska residents, particularly coastal Native Alaska communities (Ch. 26: Alaska). Winter sea ice may keep forming in a warmer world, but it could be much reduced compared to the present (see Taylor et al. 2017[2] for more details).

Annual Minimum Sea Ice Extent Decreasing

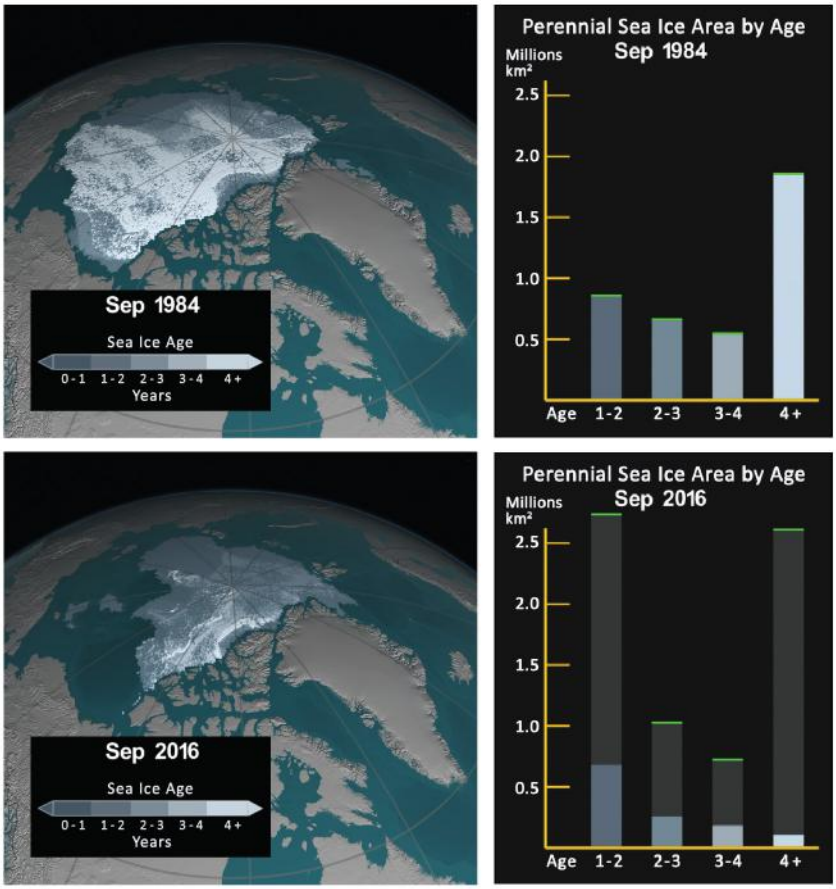

Figure A5.26: Both the extent and the age of the September sea ice cover are shown for 1984 (top) and 2016 (bottom). The colors of the bars on the right panels correspond to the colors used to indicate the age of the sea ice in the panels on the left. The green bars on the graphs on the right mark the maximum extent for each age range during the record. The year 1984 is representative of September sea ice characteristics during the 1980s. Over time, September sea ice extent and the amount of multiyear ice have greatly decreased. The years 1984 and 2016 are selected as endpoints in the timeseries. A movie of the complete time series is available at http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4489. Source: adapted from NASA 2016.[41]

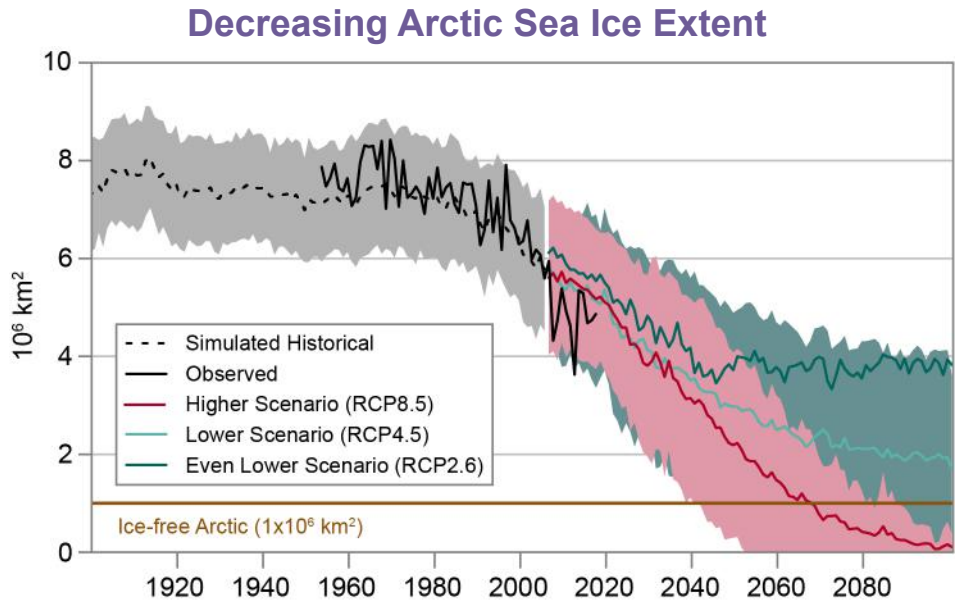

Figure A5.27: This graph shows historical simulations of arctic sea ice extent starting in 1900 (dotted black line), observations of arctic sea ice extent (solid black line), and future projections of arctic sea ice extent (colored lines) from 2005 through 2100 under three RCP scenarios. The projections shown are the average values from a set of climate model simulations, and the shaded pink and green regions indicate one-standard-deviation confidence intervals around the average values for the higher and lower scenarios, respectively. Source: adapted from Stroeve and Notz 2015.[42] ©2015 Elsevier B.V. All rights reserved.

Is Antarctica losing ice? What about Greenland?

Yes. Overall, the ice sheets on both Greenland and Antarctica, the largest areas of land-based ice on the planet, are losing ice as the atmosphere and oceans warm. This ice loss is important both as evidence that the planet is warming and because it contributes to rising sea levels.

The Antarctic ice sheet is up to three miles deep and contains enough water to raise sea level about 200 feet. Because Antarctica is so cold, there is little melting of the ice sheet, even in summer. However, the ice flows towards the ocean where above-freezing ocean water speeds up the melting process, which breaks the ice into free-floating icebergs (a process called calving). Melting, calving, and the flow of ice into the oceans around Antarctica—especially on the Antarctic Peninsula—have all accelerated in recent decades, and the result is that Antarctica is losing about 100 billion tons of ice per year (contributing about 0.01 inch per year to sea level rise; Figure A5.28).[39] While there has been slight growth in some parts of the Antarctic ice sheet, the gain is more than offset by ice mass loss elsewhere, especially in West Antarctica and along the Antarctic Peninsula. The West Antarctic ice sheet, which contains enough ice to raise global sea level by 10 feet, is likely to lose ice much more quickly if its ice shelves disintegrate. Additionally, warming oceans under the ice sheet are melting the areas where ice sheets go afloat in West Antarctica, exacerbating the risk of more rapid melt in the future.

Greenland contains only about one-tenth as much ice as the Antarctic ice sheet, but if Greenland's ice sheet were to entirely melt, global sea level would still rise about 20 feet. (For additional information on the impacts of sea level rise on the United States directly, see Ch. 8: Coastal; Ch. 18: Northeast; Ch. 19: Southeast; and Ch. 20: U.S. Caribbean.) Annual surface temperatures in Greenland are warmer than Antarctica, so melting occurs over large parts of the surface of Greenland's ice sheet each summer. Greenland's melt area has increased over the past several decades (Figure A5.28). The Greenland ice sheet is presently thinning at the edges (especially in the south) and slowly thickening in the interior, increasing the steepness of the ice sheet, which has sped up the flow of ice into the ocean over the past decade. This trend will likely continue as the surrounding ocean warms. Greenland's ice loss has increased substantially in the past decade, losing ice at an average rate of about 269 billion tons per year from April 2012 to April 2016 (contributing over 0.02 inch per year to sea level rise).[4]

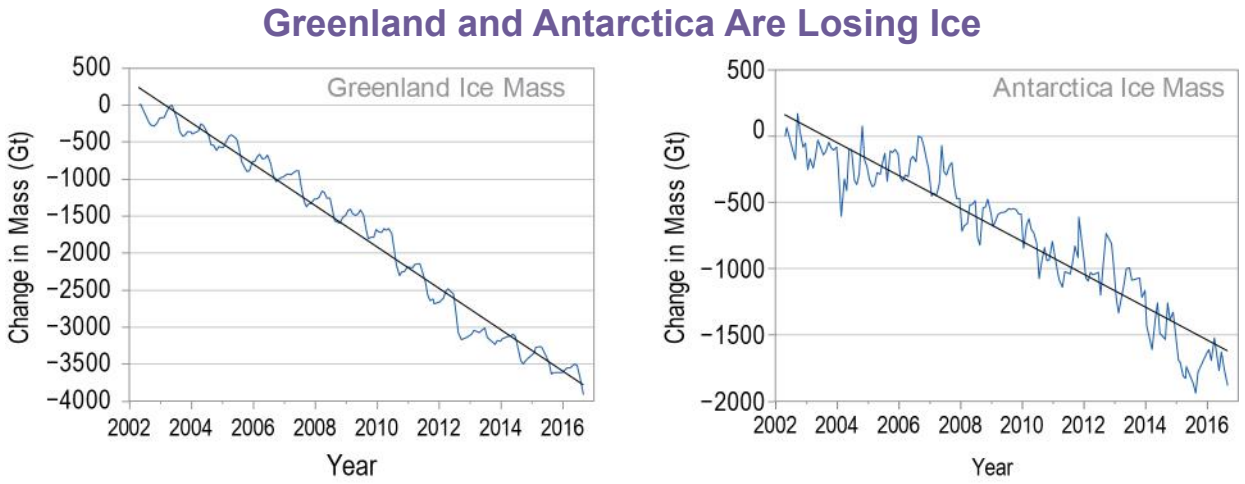

Figure A5.28: The graphs show satellite measurements of the change in ice mass for the two polar ice sheets through August 2016 as compared to April 2002. Both the Greenland and Antarctic ice sheets are losing ice as the atmosphere and oceans warm. Source: adapted from Wouters et al. 2013.[43] Reprinted by permission from Macmillan Publishers Ltd., ©2013.

How does climate change affect mountain glaciers?

Glacier retreat is one of the most important lines of evidence for global warming. Around the world, glaciers in most mountain ranges are receding at unprecedented rates. Many glaciers have disappeared altogether this century, and many more are expected to vanish within a matter of decades. Glaciers will still be around within the next century, but they will be more isolated, closer to the poles, and at higher elevations.

Glaciers are critical freshwater reservoirs that slowly release water over warmer months, which helps sustain freshwater streamflows that provide drinking and irrigation water, as well as hydropower to downstream communities. However, increasing temperatures and decreasing amounts of precipitation falling as snow are major drivers of glacial retreat (see Ch. 2: Climate; Ch. 22: N. Great Plains; Ch. 24: Northwest; Ch. 26: Alaska). Glaciers retreat when melting and evaporation outpace the accumulation of new snow. Slope, altitude, ice flow, location, and volume also contribute to the speed and extent of glacial retreat, which complicates the relationship between increasing temperature and glacial melt. Due to these local factors, not all glaciers globally are retreating. For example, melting may slow as the glaciers retreat to the upper slopes, under headwalls and steep cliffs, and into more shaded areas.

In recent decades, the mountains of Glacier National Park (GNP) in Montana have experienced an increase in summer temperatures and a reduction in the winter snowpack that forms the mountain glaciers. The annual average temperature in GNP has increased by 2.4°F since 1900, spring and summer minimum temperatures have risen, and the percentage of precipitation that comes as rain rather than snow has increased.[44,45,46] Mountain snowpacks now hold less water than they used to and have begun to melt at least two weeks earlier in the spring. This earlier melting alters glacier stability, as well as downstream water supplies, with implications for wildlife, agriculture, and fire management.

In a recent study, scientists looked at 39 glaciers in and around GNP and compared aerial photos and digital maps from 1966 to 2016. Currently, only 26 glaciers are bigger than 25 acres, the minimum size used for defining a glacier. When GNP was established early in 1910, it is estimated that there were 150 glaciers larger than 25 acres. Long-term studies of glacier size have shown that the rate of melting has fluctuated in response to decade-long climate cycles and that the melting rate has risen steeply since about 1980.[47,48] Over the next 30 years, glaciologists project that most glaciers in GNP will melt to a point where they are too small to be active glaciers, and some may disappear completely. All glaciers in the park are under severe threat of completely melting by the end of the century.[4]

How are the oceans affected by climate change?

The oceans have absorbed over 90% of the excess heat energy and more than 25% of the carbon dioxide (CO_2) that is trapped in the atmosphere as a result of human-produced greenhouse gases (GHGs). Due to this increase in GHGs in the atmosphere, all ocean basins are warming and experiencing changes in their circulation and seawater chemistry, all of which alter ecosystem structure and marine biodiversity.

The world's oceans have been and will continue to be impacted by climate change. More than 50% of the world's marine ecosystems are already exposed to conditions (temperature, oxygen, salinity, and pH) that are outside the normal range of natural climate variability, and this percentage will rise as the planet warms (Ch. 9: Oceans).[1] Global warming will alter the ability of species to survive and can reorganize ecosystems, creating novel habitats and/or reducing biodiversity. Some species are responding to increased ocean temperatures by shifting their geographic ranges, generally to higher latitudes, or altering the timing of life stages (for example, spawning; Figure A5.29) (see Ch. 7: Ecosystems; Ch. 18: Northeast).[49] Other species are unable to adapt as their habitats deteriorate (for example, due to loss of sea ice) or the rate of climate-related changes occurs faster than they can move (for example, in the case of sessile organisms, such as oysters and corals).

Physical changes to the ocean system will also occur. Observations and projections suggest that in the next 100 years, the Gulf Stream (part of the larger "ocean conveyor belt") could slow down as a result of climate change, which could increase regional sea level rise and alter weather patterns along the U.S. East Coast.[13,50]

In addition to causing changes in temperature, precipitation, and circulation, increasing atmospheric levels of CO_2 have a direct effect on ocean chemistry. The oceans currently absorb about a quarter of the 10 billion tons of CO_2 emitted to the atmosphere by human activities every year. Dissolved CO_2 reacts with seawater to make it more acidic. This acidification impacts marine life such as shellfish and corals, making it more difficult for these calcifying animals to make their hard external structures (Ch. 8: Oceans; Ch. 24: Northwest).

Over the last 50 years, inland seas, estuaries, and coastal and open oceans have all experienced major oxygen losses. A warmer ocean holds less oxygen. Warming also changes the physical mixing of ocean waters (for example, upwelling and circulation) and can interact with other human-induced changes. For example, fertilizer runoff entering the Gulf of Mexico through the Mississippi River can stimulate harmful algal blooms. These blooms eventually decay, creating large "dead zones" of water with very low oxygen, where animals cannot survive. Warmer conditions slow down the rate at which this oxygen can be replaced, exacerbating the impact of the dead zone. These are just a few of the changes projected to occur, as detailed in Chapter 9: Oceans.

Projected Changes in Maximum Fish Catch Potential

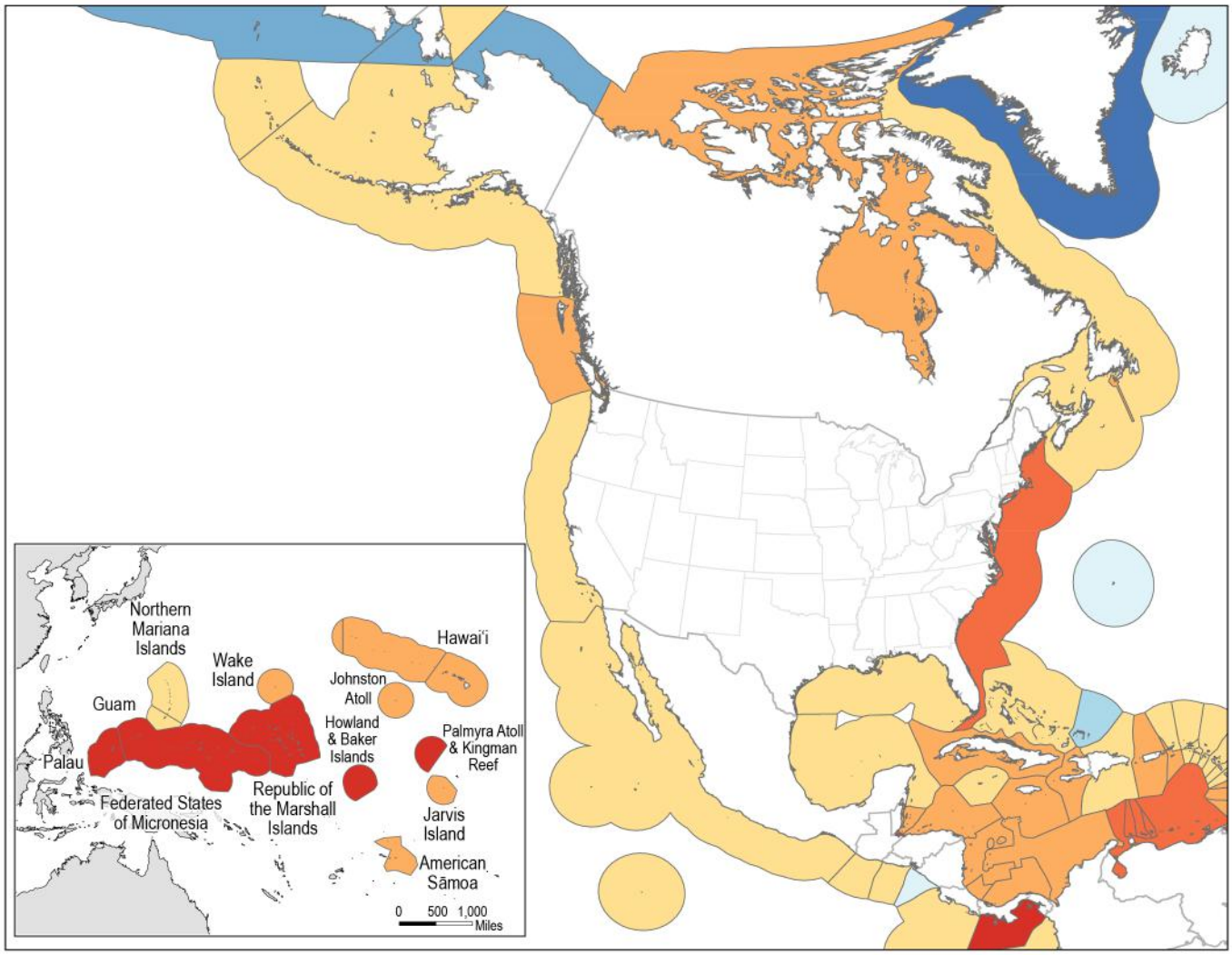

Figure A5.29: The figure shows average projected changes in fishery catches within large marine ecosystems for 2041–2060 relative to 1991–2010 under a higher scenario (RCP8.5). All U.S. large marine ecosystems, with the exception of the Alaska Arctic, are expected to see declining fishery catches. Source: adapted from Lam et al. 2016.[51]

What is ocean acidification, and how does it affect marine life?

The oceans currently absorb more than a quarter of the 10 billion tons of carbon dioxide (CO_2) released annually into the atmosphere from human activities. CO_2 reacts with seawater to form carbonic acid, so more dissolved CO_2 increases the acidity of ocean waters. When seawater reaches a certain acidity, it eats away at, or corrodes, the shells and skeletons made by shellfish, corals, and other species—or impedes the ability of organisms to grow them in the first place.

Since the beginning of the Industrial Revolution, the acidity of surface ocean waters has increased approximately 30%. The oceans will continue to absorb CO_2 produced by human activities, causing acidity to rise further (Figure A5.30). Ocean waters are not acidifying at the same rate around the globe, largely due to differences in ocean temperature. Warmer, low-latitude waters naturally hold less CO_2 and therefore tend to be less acidic. Colder, high-latitude waters naturally hold more CO_2, have increased acidity, and are closer to the threshold where shells and skeletons tend to corrode. Coastal and estuarine waters are also acidified by local phenomena, such as freshwater runoff from land, nutrient pollution, and upwelling.[1]

In the past five years, scientists have found that the shells of small planktonic snails (called pteropods) are already partially dissolved in locations where ocean acidification has made ocean waters corrosive, such as in the Pacific Northwest and near Antarctica. Pteropods are an important food source for Pacific salmon, so impacts to pteropods could cause changes up the food chain. Acidification has also affected commercial oyster hatcheries in the Pacific Northwest, where acidified waters impaired the growth and survival of oyster larvae (Ch. 24: Northwest).

Because marine species vary in their sensitivity to ocean acidification, scientists expect some species to decline and others to increase in abundance in response to this environmental change. Relative changes in species performance can ripple through the food web, reorganizing ecosystems as the balance between predators and prey shifts and habitat-forming species increase or decline. Habitat-forming species, such as corals and oysters, that grow by using minerals from the seawater to build mass are particularly vulnerable. It is difficult to predict exactly how ocean acidification will change ecosystems. Scientists and managers are now using computer models to project potential consequences to fisheries, protected species, and habitats (see Ch. 9: Oceans for more details).

Projected Change in Surface Ocean Acidity

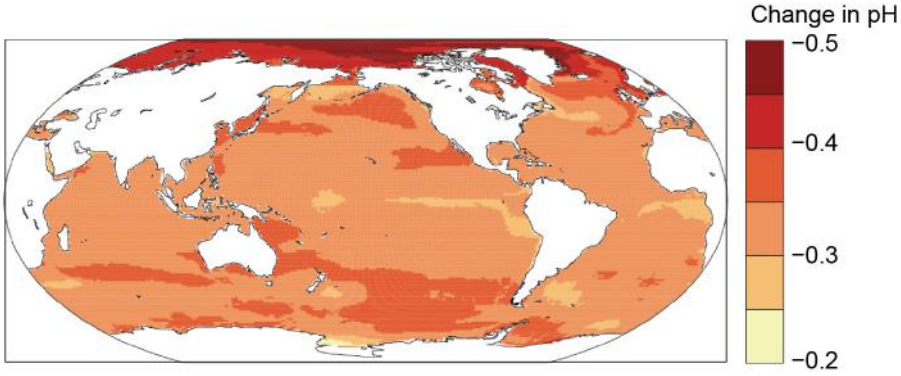

Figure A5.30: This figure shows projected changes in sea surface pH in 2090–2099 relative to 1990–1999 under the higher scenario (RCP8.5). As shown in the figure, every ocean is expected to increase in acidity, with increases in the Arctic Ocean projected to become the most pronounced. Source: adapted from Bopp et al. 2013 (CC BY 3.0).[52]

How do higher carbon dioxide concentrations affect plant communities and crops?

Plant communities and crops respond to higher atmospheric carbon dioxide concentrations in multiple ways. Some plant species are more responsive to changes in carbon dioxide than others, which makes projecting changes difficult at the plant community level. For approximately 95% of all plant species, an increase in carbon dioxide represents an increase in a necessary resource and could stimulate growth, assuming other factors like water and nutrients are not limiting and temperatures remain in a suitable growing range.

Along with water, nutrients, and sunlight, carbon dioxide (CO_2) is one of four resources necessary for plants to grow. At the level of a single plant, all else being equal, an increase in CO_2 will tend to accelerate growth because of accelerated photosynthesis, but a plant's ability to respond to increased CO_2 may be limited by soil nutrients. Exactly how much growth stimulation will occur varies significantly from species to species. However, the interaction between plants and their surrounding environment complicates the relationship. As CO_2 increases, some species may respond to a higher degree and become more competitive, which may lead to changes in plant community composition. For example, loblolly pine and poison ivy both grow in response to elevated CO_2; however, poison ivy responds more and becomes more competitive.[53]

The expected effects of increased CO_2 in agricultural plants are in line with these same patterns. Some crops that are not experiencing stresses from nutrients, water, or biotic stresses such as pests and disease are expected to benefit from CO_2 increases in terms of growth. However, the quality of those crops can suffer, as rising levels of atmospheric CO_2 can decrease dietary iron and other micronutrients (Ch. 14: Human Health). Plants often become less water stressed as CO_2 levels increase, because high atmospheric CO_2 allows plants to photosynthesize with lower water losses and higher water-use efficiencies. The magnitude of the effect varies greatly from crop to crop. However, for many crops in most U.S. regions, the benefits will likely be mostly or completely offset by increased stresses, such as higher temperatures, worsening air quality, and decreased ground moisture (Ch. 10: Ag & Rural). If crops and weeds are competing, then rising CO_2, in general, is more likely to stimulate the weed than the crop, with negative effects on production unless weeds are controlled.[54] Controlling weeds, however, is slightly more difficult, as rising CO_2 can reduce the efficacy of herbicides through enhanced gene transfer between crops and weedy relatives.[54]

Downstream impacts of rising CO_2 on plants can be significant. Increasing CO_2 concentrations provide an opportunity for cultivators to select plants that can exploit the higher CO_2 conditions and convert it to additional seed yield.[55] However, an area of emerging science suggests that rising CO_2 can reduce the nutritional quality (protein and micronutrients) of major crops.[56] In addition, rising CO_2 can reduce the protein concentration of pollen sources for bees.[57] Climate change also influences the amount and timing of pollen production. Increased CO_2 and temperature are correlated with earlier and greater pollen production and a longer allergy season (Ch. 13: Air Quality).

Please see Chapter 10: Ag & Rural, Chapter 6: Forests, and Ziska et al. (2016)[56] for more information on how climate change affects crops and plants.

Is climate change affecting U.S. wildfires?

It is difficult to determine how much of a role climate change has played in affecting recent wildfire activity in the United States. However, climate is generally considered to be a major driver of wildfire area burned. Over the last century, wildfire area burned in the mountainous areas of the western United States was greater during periods of low precipitation, drought, and high temperatures. Increased temperatures and drought severity with climate change will likely lead to increased fire area burned in fire-prone regions of the United States.

Climate is a major determinant of vegetation composition and productivity, which directly affect the type, amount, and structure of fuel available for fires. Climate also affects fuel moisture and the length of the season when fires are likely. Higher temperatures and lower precipitation result in lower fuel moisture, making fire spread more likely when an ignition occurs (if fuel is available). In mountainous areas, higher temperatures, lower snowpack, and earlier snowmelt lead to a longer fire season, lower fuel moisture, and higher likelihood of large fires.[58,59] Forest management practices are also a factor in determining the likelihood of ignition, as well as fire duration, extent, and intensity (Ch. 6: Forests).[23]

Long records of fire provided by tree-ring and charcoal evidence show that climate is the primary driver of fire on timescales ranging from years to millennia.[60] During the 20th century in the western United States, warm and dry conditions in spring and summer generally led to greater area burned in most places, particularly more mountainous and northerly locations (Figure A5.31).[60] The frequency of large forest fires (greater than 990 acres) has increased since the 1970s in the Northwest (1,000%) and Northern Rocky Mountains (889%), followed by forests in the Southwest (462%), Southern Rocky Mountains (274%), and Sierra Nevada (256%).[59] Dry forests in these regions account for about half of the total forest area burned since 1984. Globally, the length of the fire season (the time of year when climate and weather conditions are conducive to fire) has increased by 19% between 1979 and 2013, and it has become significantly longer over this period in most of the United States.[61]

With climate change, higher temperatures and more severe drought will likely lead to increased area burned in many ecosystems of the western and southeastern United States. By the mid-21st century, annual area burned is expected to increase 200%–300% in the contiguous western United States and 30% in the southeastern United States.[62] Over time, warmer temperatures and increased area burned can alter vegetation composition and productivity, which in turn affect fire occurrence. In arid regions, vegetation productivity may decrease sufficiently that fire will become less frequent. In other regions, climate may become less of a limiting factor for fire, and fuels may become more important in determining fire severity and extent.[63] In a warmer climate, wildfire is expected to be a catalyst for ecosystem change in all fire-prone ecosystems.

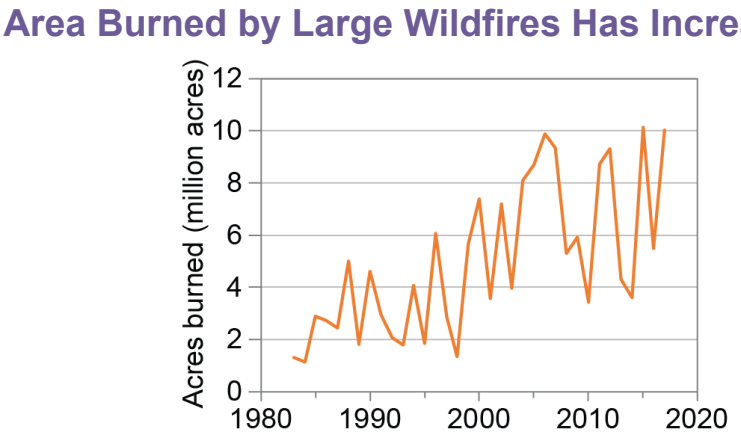

Figure A5.31: The figure shows the annual area burned by wildfires in the United States from 1983 to 2017. Warmer and drier conditions have contributed to an increase in large forest fires in the western United States and interior Alaska over the past several decades, and the ten years with the largest area burned have all occurred since 2000. Source: adapted from EPA 2016.[64]

Does climate change increase the spread of mosquitoes or ticks?

Yes. Climate change can contribute to the spread of mosquitoes and ticks. A warmer climate enhances the suitability of habitats that were formerly too cold to support mosquito and tick populations, thus allowing these vectors, and the diseases they transmit, to invade new areas.

Mosquitoes and ticks are dependent on external sources for body heat, thus they develop from egg to adult more quickly under warmer conditions, producing more generations in a shorter time. Warming also speeds up population growth of the parasites and pathogens that mosquitoes transmit (including the agents of Zika virus, dengue fever, West Nile virus, and malaria), as well as the rate at which mosquitoes bite people and other hosts. Additionally, warmer conditions facilitate the spread of mosquitoes by increasing the length of the growing season and by decreasing the likelihood of winter die-offs due to extreme cold (Ch. 14: Human Health).[65]

Blacklegged (deer) ticks are the main vector (or transmitter) of Lyme disease in the United States. These ticks require a minimum number of days above freezing to persist. As a result, some northern and high-elevation areas cannot be invaded because the warm season is too short to allow each life stage to find an animal host before it needs to retreat underground. But as higher-latitude and higher-altitude areas continue to warm, blacklegged ticks may expand their range northward and higher in elevation (Figure A5.32) (see also Ch. 14: Human Health).[66,67] Studies show that ticks emerge earlier in the spring under warmer conditions, suggesting that the main Lyme disease season will move earlier in the spring.[65] Thus, earlier onset of warm spring conditions and warm summers and falls increase the establishment and resilience of tick populations.

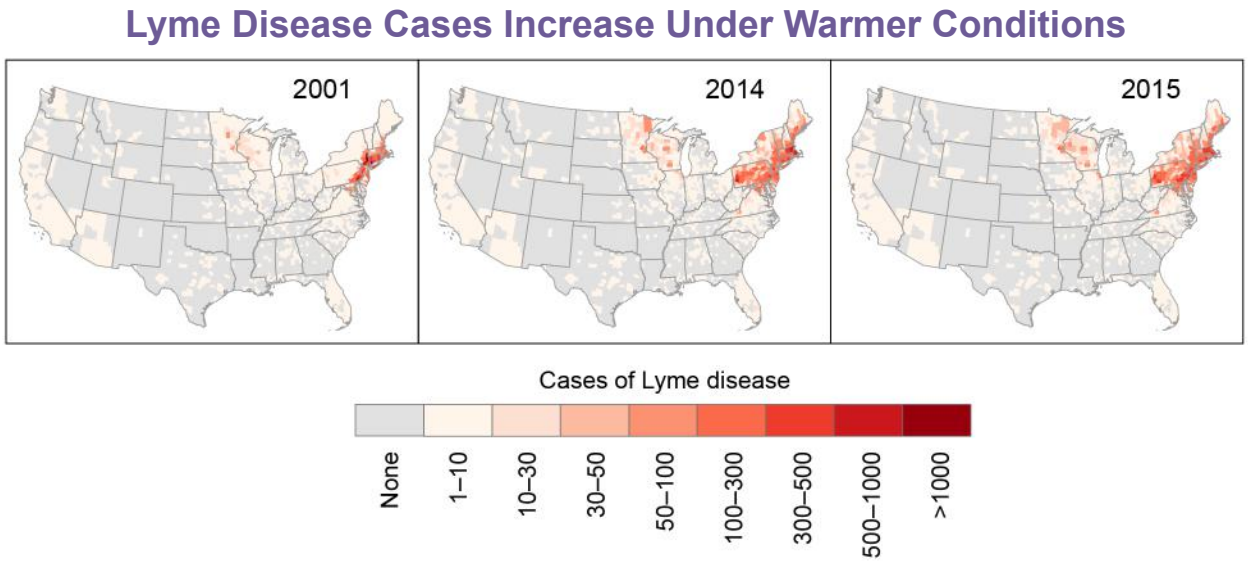

Figure A5.32: Reported cases of Lyme disease in 2001, 2014, and 2015 are shown by county for the contiguous United States. Both the distribution and total number of cases have increased from 2001 to 2014 and 2015, particularly in the Midwest and Northeast. Sources: CDC and ERT, Inc.

Acknowledgments

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