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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Front cover: *National Park Service;* **back cover:** *NASA Earth Observatory image by Joshua Stevens, using Landsat data from the U.S. Geological Survey.*

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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First published 2018

Printed in the United States of America

Recommended Citation

USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1506 pp. doi: 10.7930/NCA4.2018

Published by U.S. Government Publishing Office

Internet: bookstore.gpo.gov; Phone: toll free (866) 512-1800; DC area (202) 512-1800

Fax: (202) 512-2104 Mail: Stop IDCC, Washington, DC 20402-0001

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NCA4

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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 V and II. RCPs focus on outputs (such as emis- sions and concentrations of greenhouse gases and particulate matter) that are in turn fed into climate models. As such, a wide range of fu- ture 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.

National Climate Assessment Regions

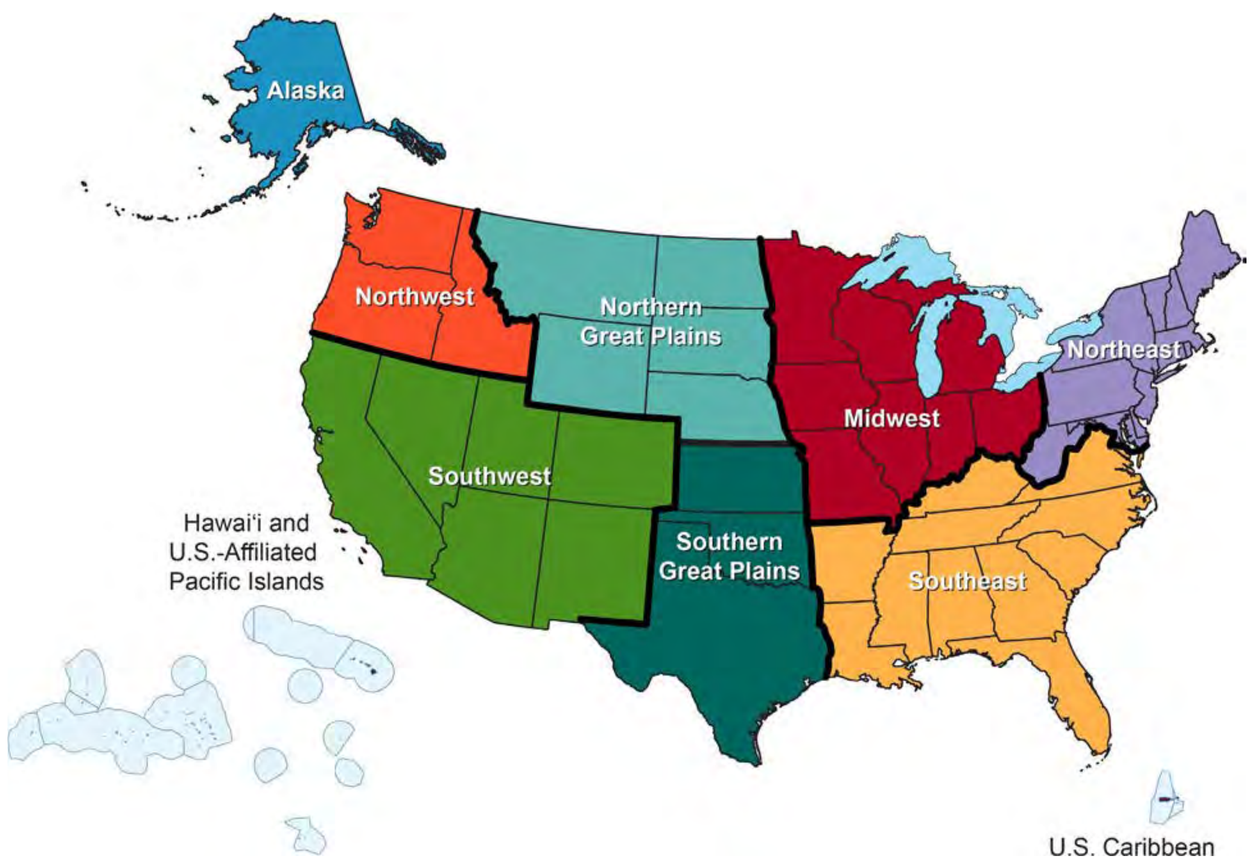

Figure 1: Map of the ten regions used throughout NCA4.

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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Recommended Citation for Chapter

Jay, A., D.R. Reidmiller, C.W. Avery, D. Barrie, B.J. DeAngelo, A. Dave, M. Dzaugis, M. Kolian, K.L.M. Lewis, K. Reeves, and D. Winner, 2018: Overview. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 24–62. doi: 10.7930/NCA4.2018.CH1

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

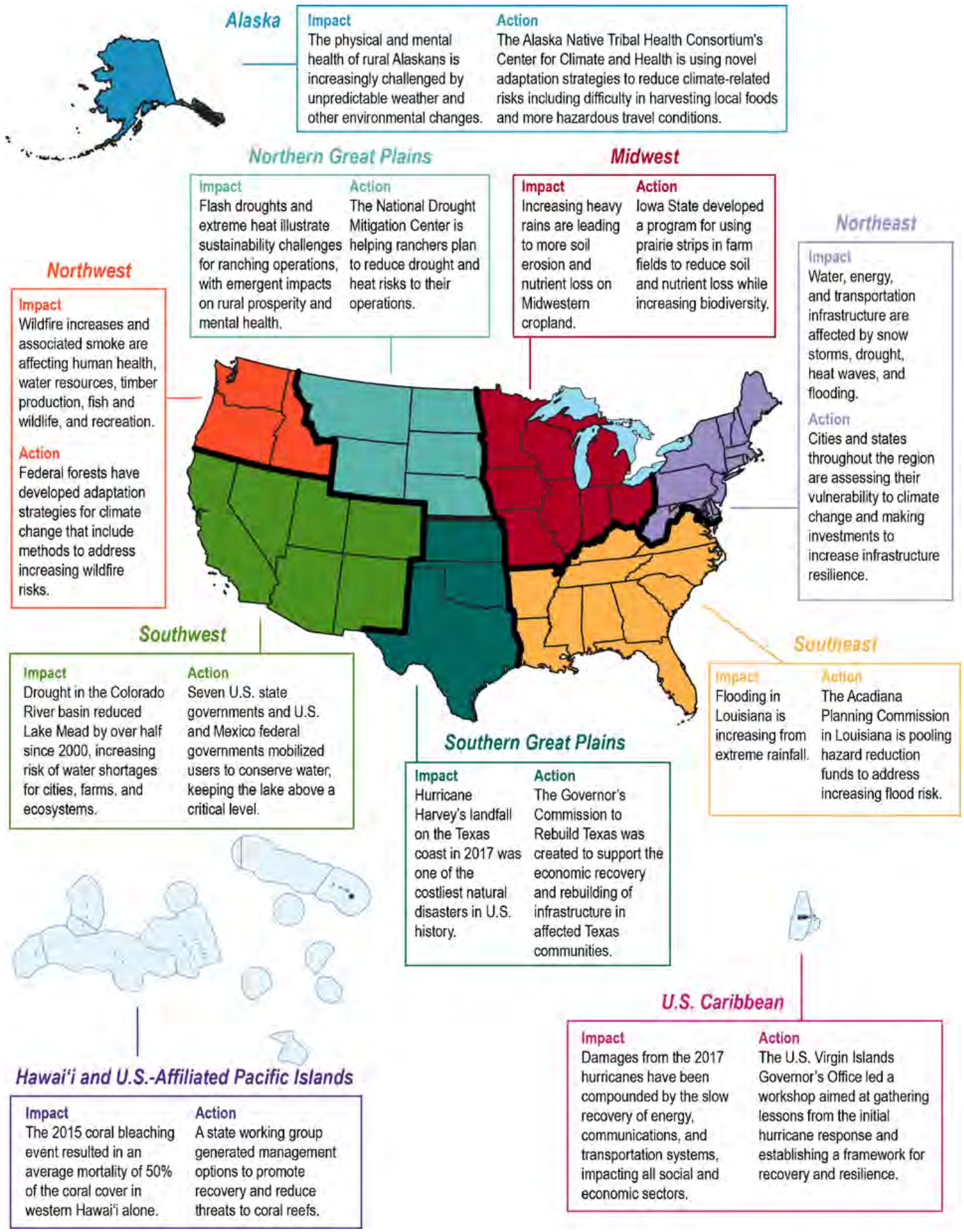


Figure 1.1: This map shows climate-related impacts that have occurred in each region since the Third National Climate Assessment in 2014 and response actions that are helping the region address related risks and costs. These examples are illustrative; they are not indicative of which impact is most significant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

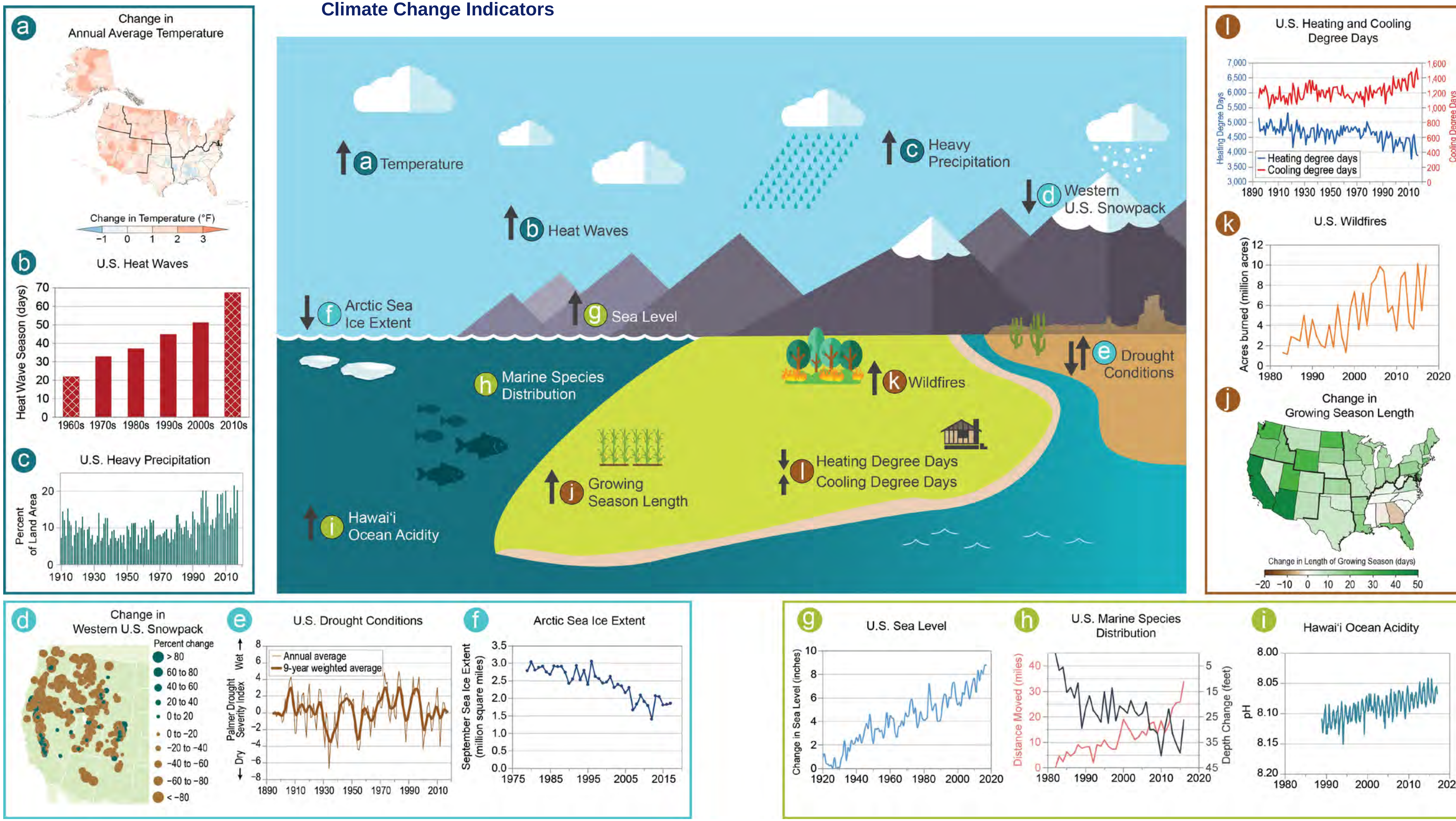


Figure 1.2: Long-term observations demonstrate the warming trend in the climate system and the effects of increasing atmospheric greenhouse gas concentrations (Ch. 2: Climate, Box 2.2). This figure shows climate-relevant indicators of change based on data collected across the United States. Upward-pointing 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

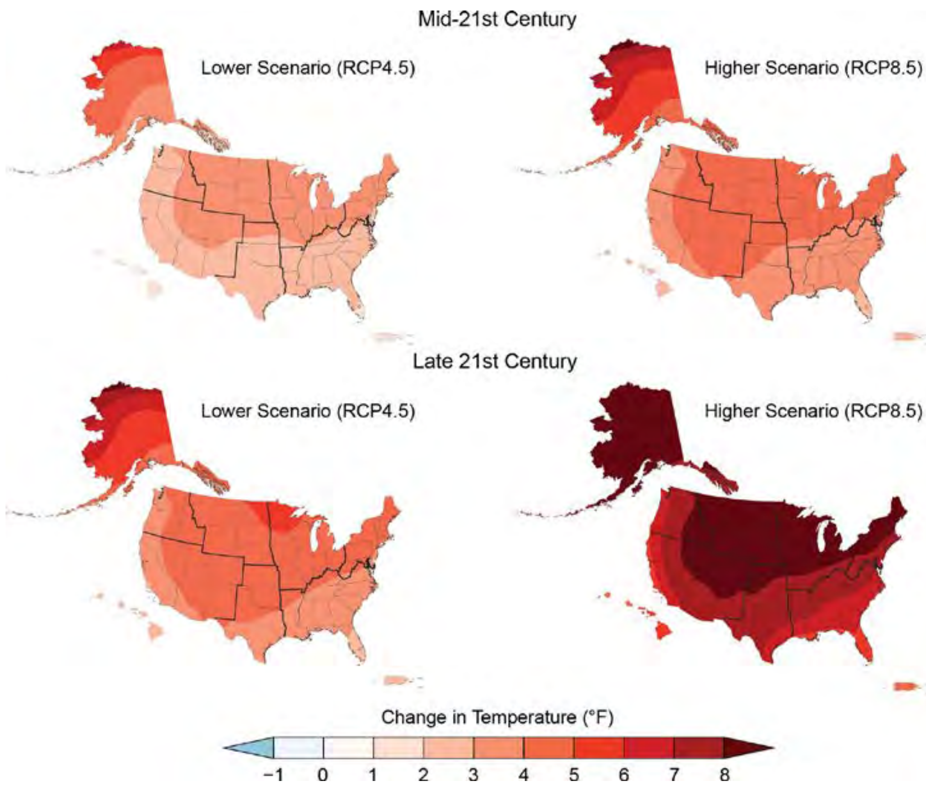


Figure 1.3: Annual average temperatures across the United States are projected to increase over this century, with greater changes at higher latitudes as compared to lower latitudes, and under a higher scenario (RCP8.5; right) than under a lower one (RCP4.5; left). This figure shows projected differences 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

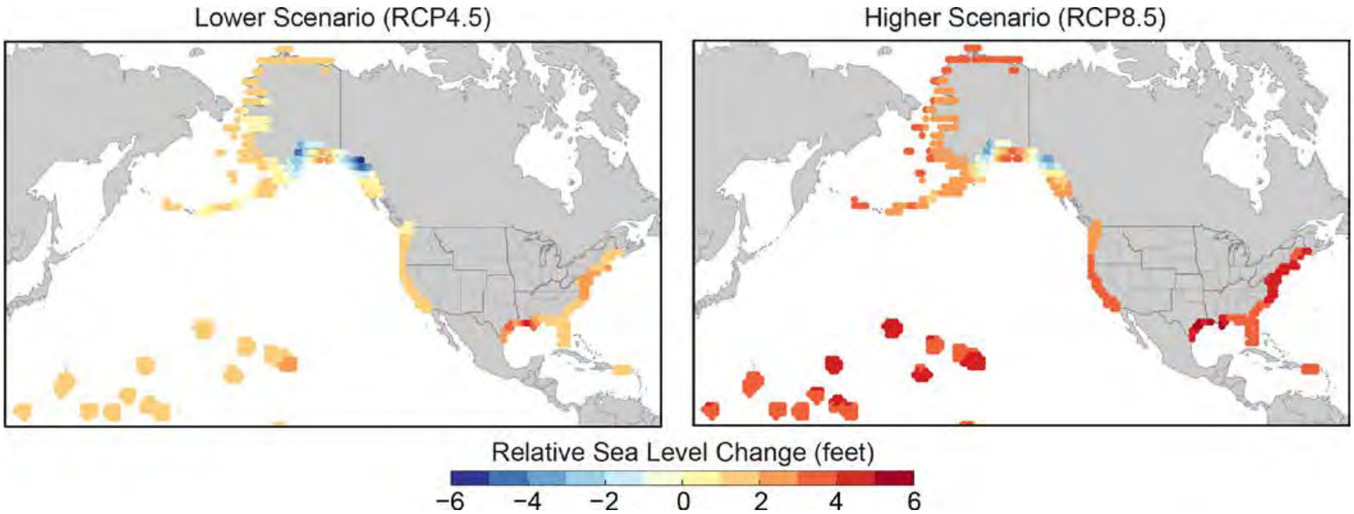


Figure 1.4: The maps show projections of change in relative sea level along the U.S. coast by 2100 (as compared to 2000) under the lower (RCP4.5) and higher (RCP8.5) scenarios (see CSSR, Ch. 12.5). Globally, sea levels will continue to rise from thermal expansion of the ocean and melting of land-based 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 Hawaiʻi and the U.S.-Affiliated Pacific Islands (Ch. 26: Alaska, KM 2; Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawaiʻi & 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 sealevels and stronger hurricanes; regional disruptions are expected to have national implications (Ch. 4: Energy, State of the Sector, KM 1; Ch.

Weather and Climate-Related Impacts on U.S. Military Assets

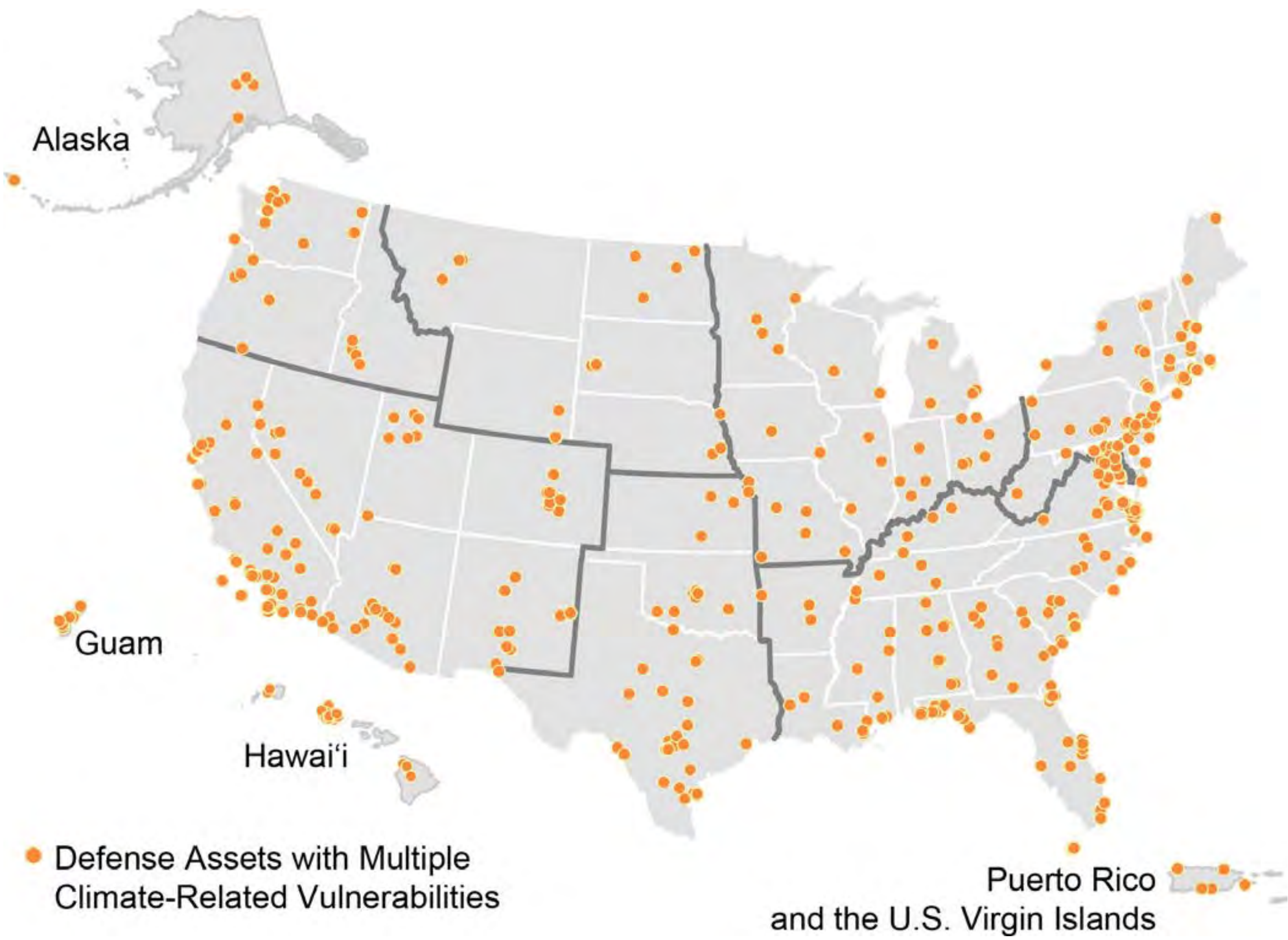


Figure 1.9: The Department of Defense (DoD) has significant experience in planning for and managing risk and uncertainty. The effects of climate and extreme weather represent additional risks to incorporate into the Department's various planning and risk management processes. To identify DoD installations 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.

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).*

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).

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 Environmentand 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

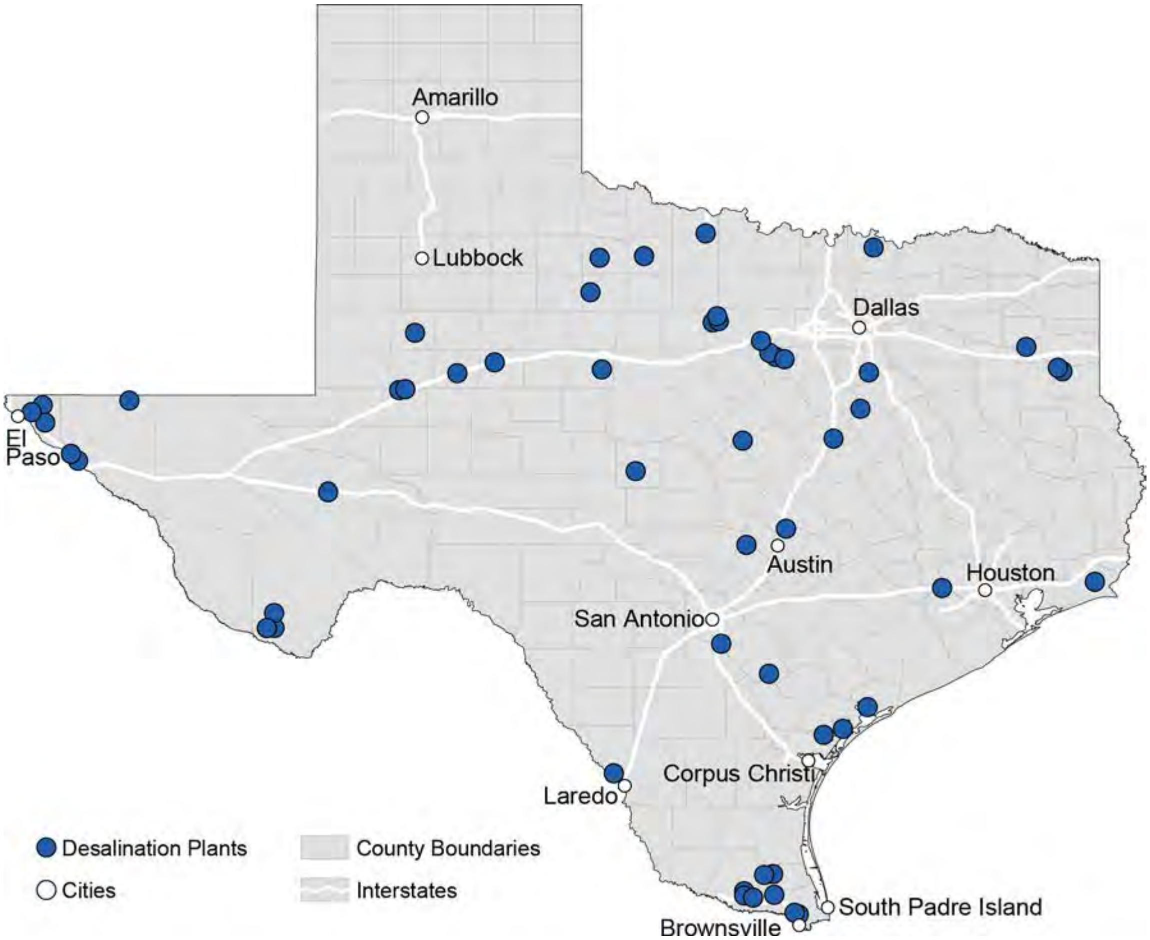


Figure 1.12: Desalination activities in Texas are an important contributor to the state's efforts to meet current and projected water needs for communities, industry, and agriculture. The state's 2017 Water Plan recommended an expansion of desalination to help reduce longer-term risks to water supplies 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

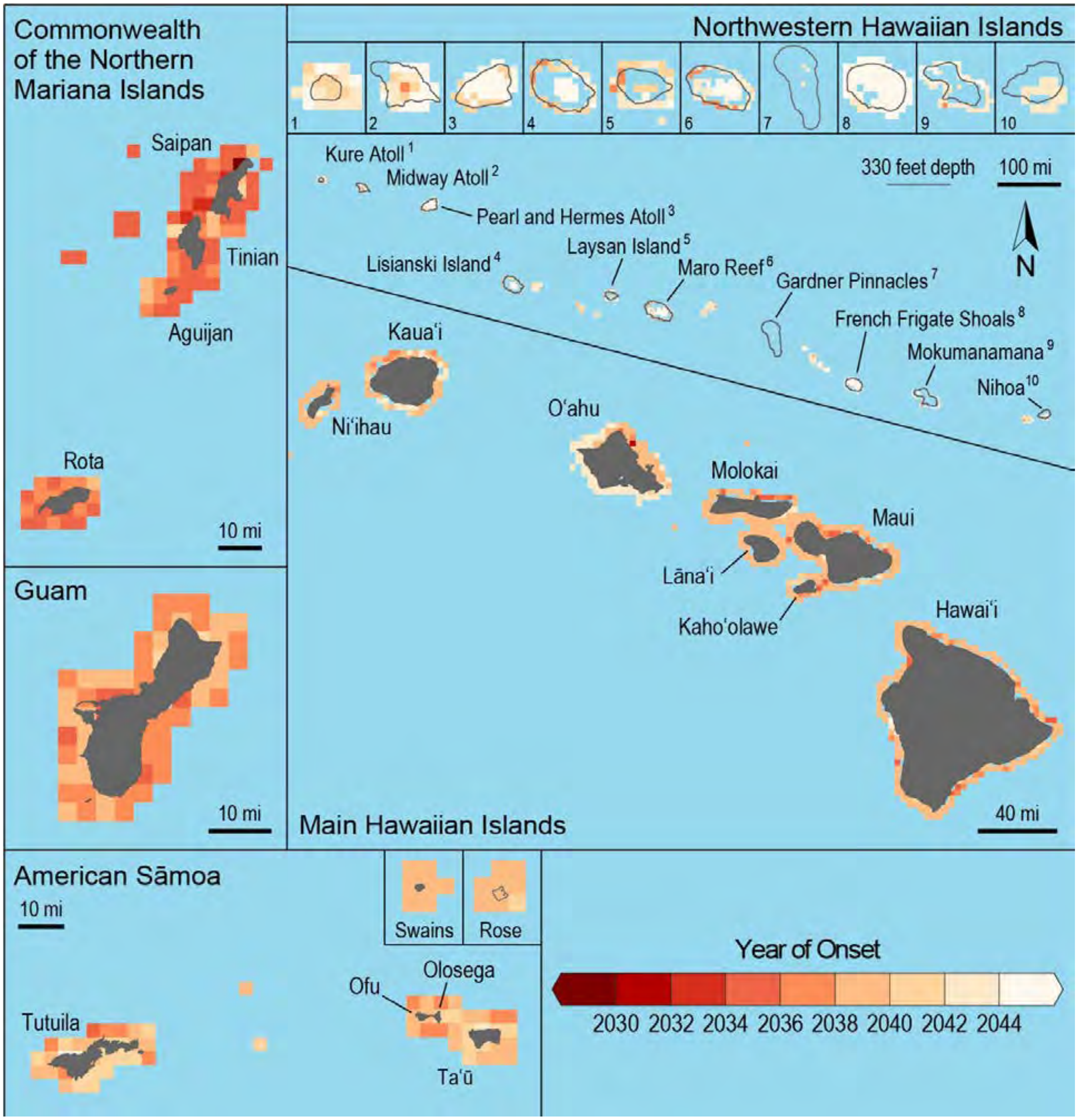


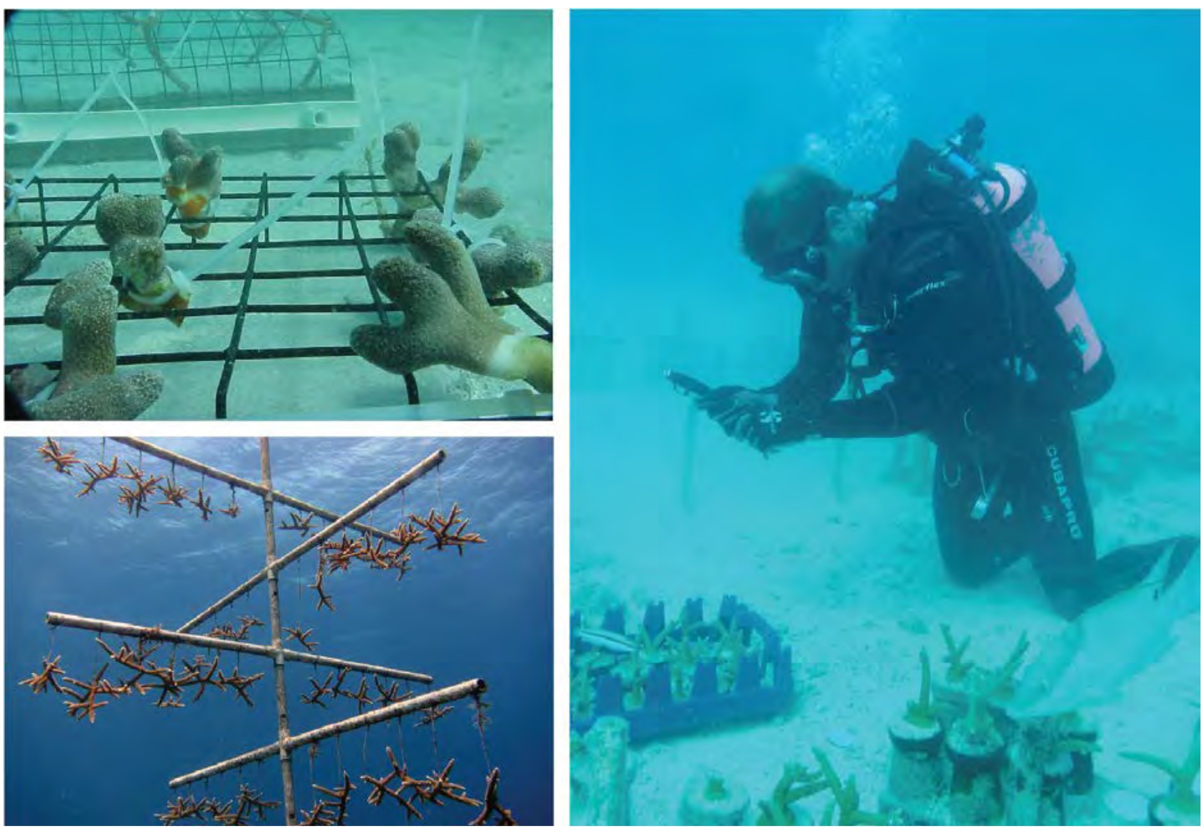
Figure 1.14: The figure shows the years when severe coral bleaching is projected to occur annually in the Hawai‘i and U.S.-Affiliated Pacific Islands region under a higher scenario (RCP8.5). Darker colors indicate earlier projected onset of coral bleaching. Under projected warming of approximately 0.5°F 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

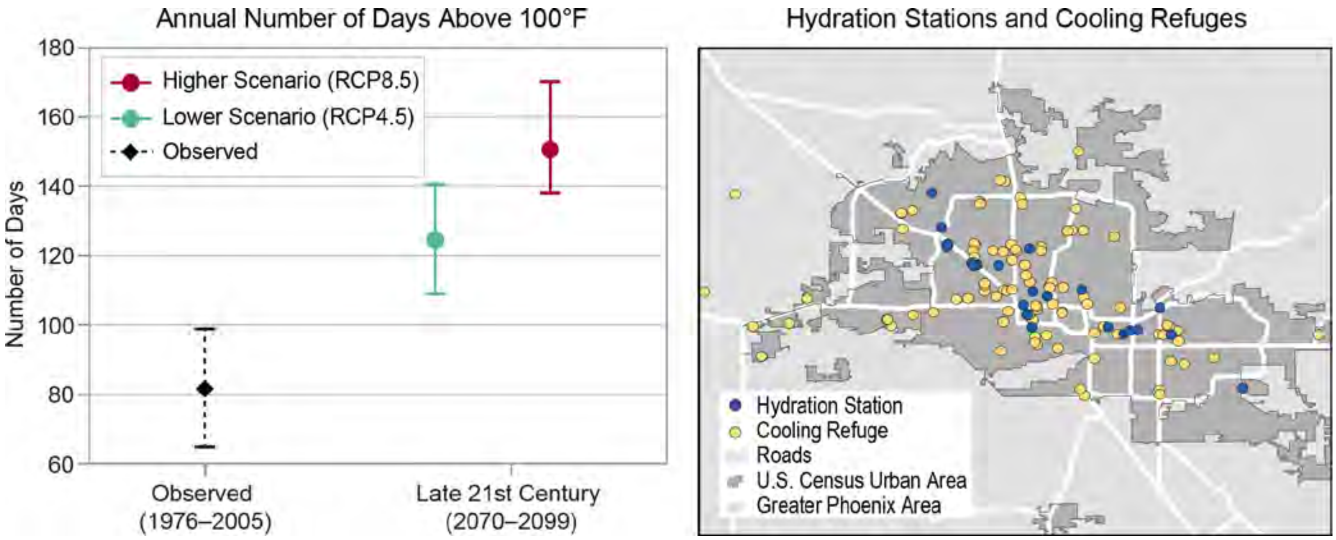


Figure 1.16: (left) The chart shows the average annual number of days above 100°F in Phoenix, Arizona, for 1976–2005, and projections of the average number of days per year above 100°F through the end of the 21st century (2070–2099) under the lower (RCP4.5) and higher (RCP8.5) scenarios. Dashed lines 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).

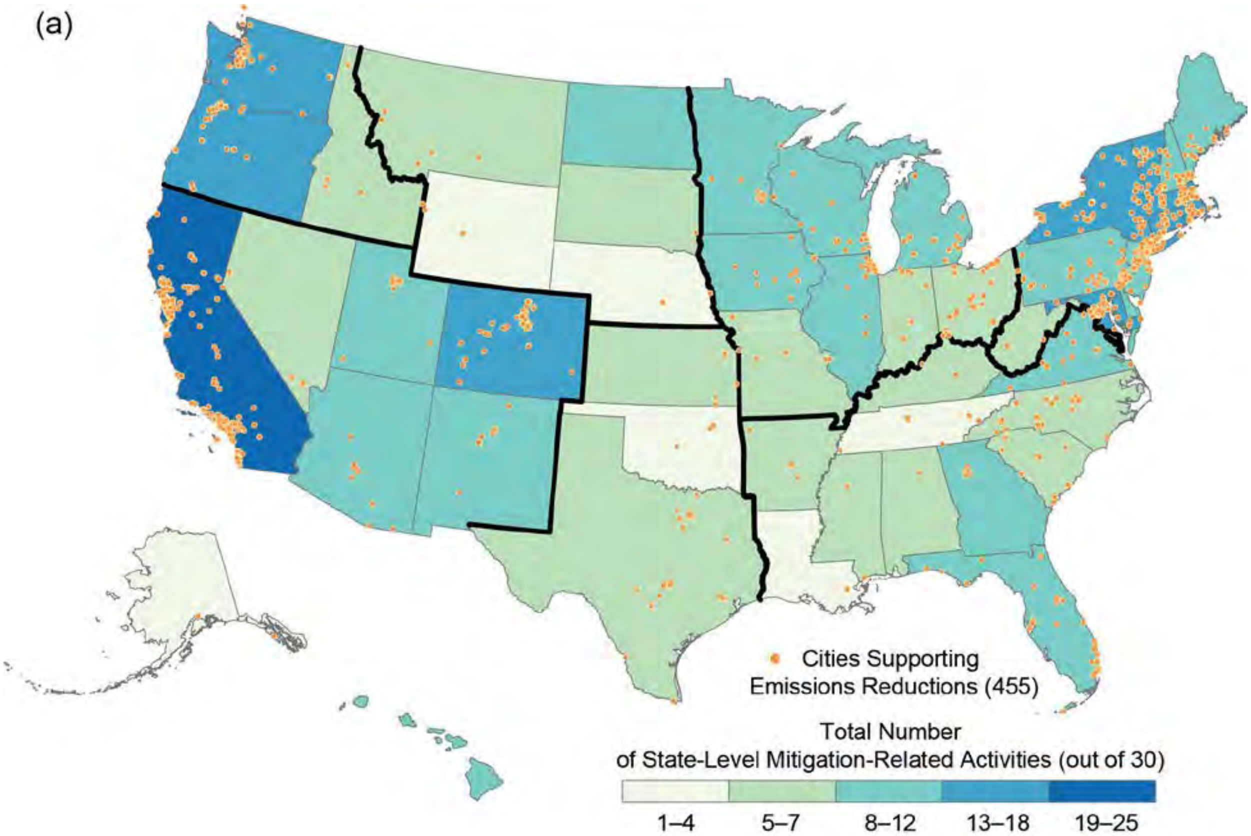
Since the Third National Climate Assessment (NCA3) in 2014, a growing number of states, cities, and businesses have pursued or expanded upon initiatives aimed at reducing greenhouse gas emissions, and the scale of adaptation implementation across the country has increased. However, these efforts do not 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



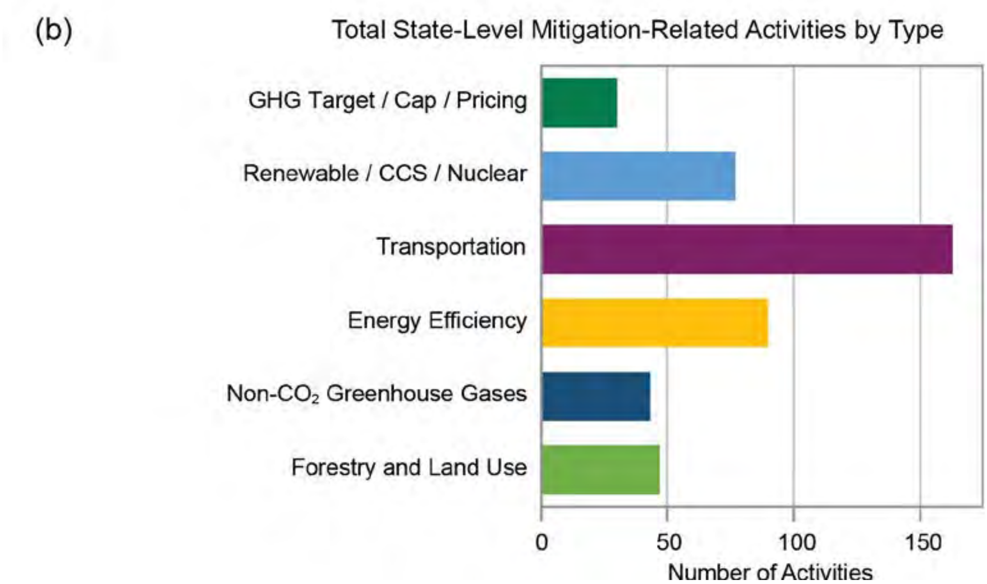


Figure 1.19: (a) The map shows the number of mitigation-related activities at the state level (out of 30 illustrative activities) as well as cities supporting emissions reductions; (b) the chart depicts the type and number of activities by state. Several territories also have a variety of mitigation-related 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

Five Adaptation Stages and Progress

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).

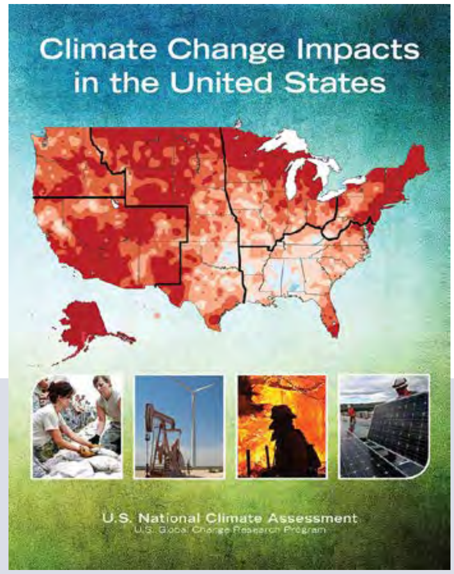
A significant portion of climate risk can be addressed by integrating climate adaptation into existing investments, policies, and practices. Integration of climate adaptation into decision processes has begun in many areas including financial risk reporting, capital investment planning, engineering standards, 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 Hawaiʻi 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 Hawaiʻi, 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.

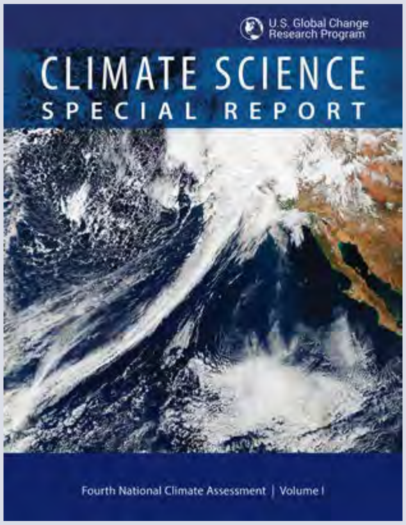
Tornadoes: In March 2017, a severe tornado outbreak caused damage across much of the Midwest and into the Northeast. Nearly 1 million customers lost power in Michigan alone due to sustained high winds, which affected several states from Illinois to New York.

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

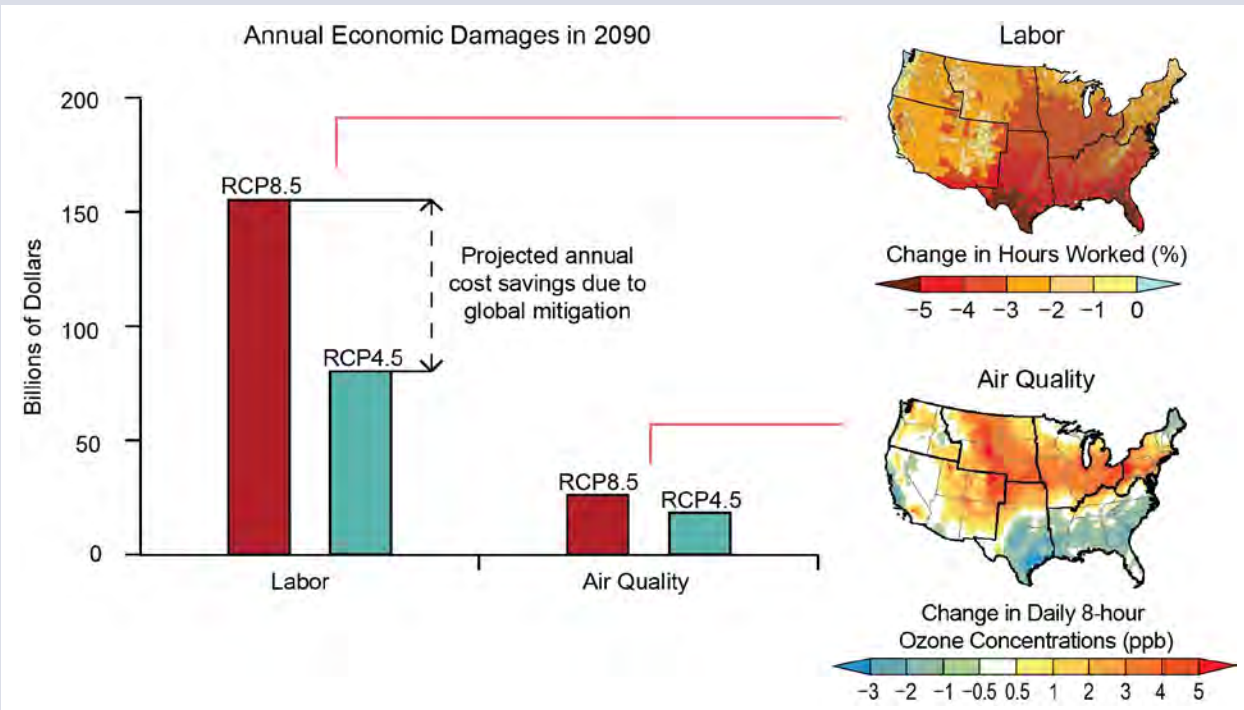


Figure 1.21: Annual economic impact estimates are shown for labor and air quality. The bar graph on the left shows national annual damages in 2090 (in billions of 2015 dollars) for a higher scenario (RCP8.5) and lower scenario (RCP4.5); the difference between the height of the RCP8.5 and RCP4.5 bars 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, EPA430-R-17-001.*

2 Our Changing Climate

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Recommended Citation for Chapter

Hayhoe, K., D.J. Wuebbles, D.R. Easterling, D.W. Fahey, S. Doherty, J. Kossin, W. Sweet, R. Vose, and M. Wehner, 2018: Our Changing Climate. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 63–135. doi: 10.7930/NCA4.2018.CH2

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

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 1.2ºF (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

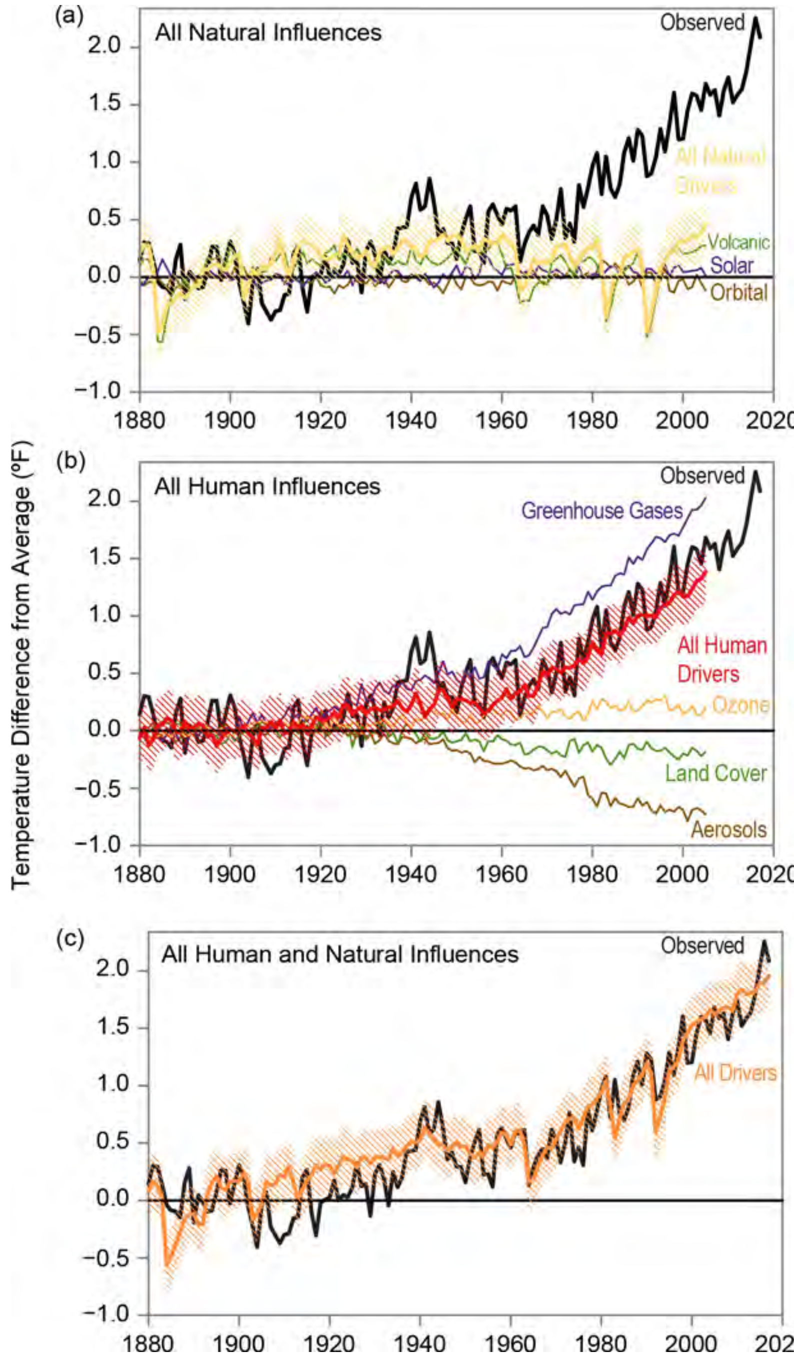

Figure 2.1: Both human and natural factors influence Earth's climate, but the long-term global warming trend observed over the past century can only be explained by the effect that human activities have had on the climate.

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

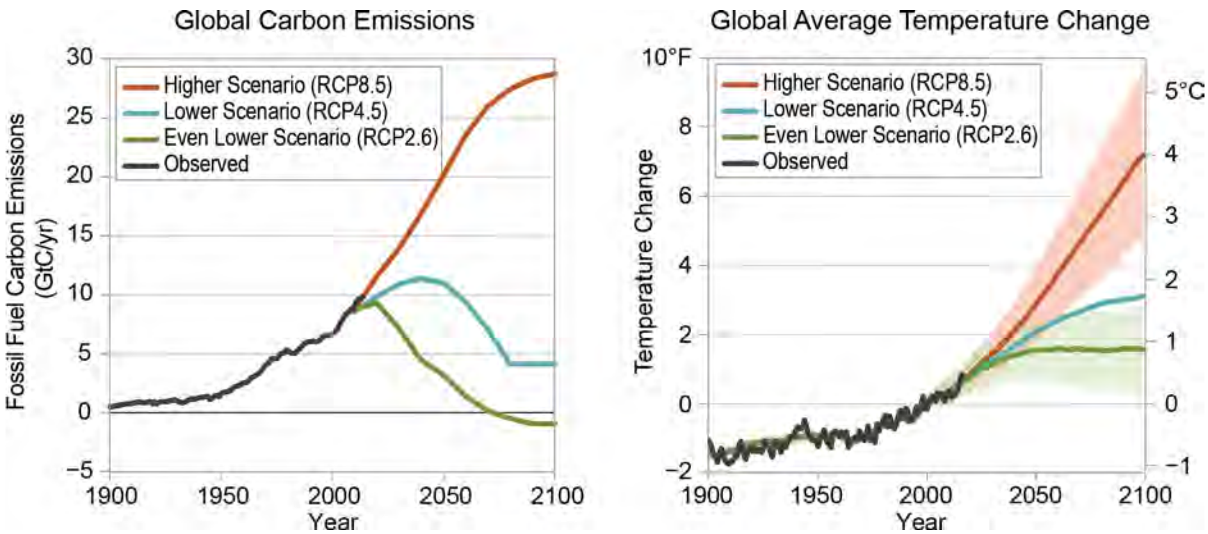

Figure 2.2: Observed and projected changes in global average temperature (right) depend on observed and projected emissions of carbon dioxide from fossil fuel combustion (left) and emissions of carbon dioxide and other heat-trapping gases from other human activities, including land use and land-use change. 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

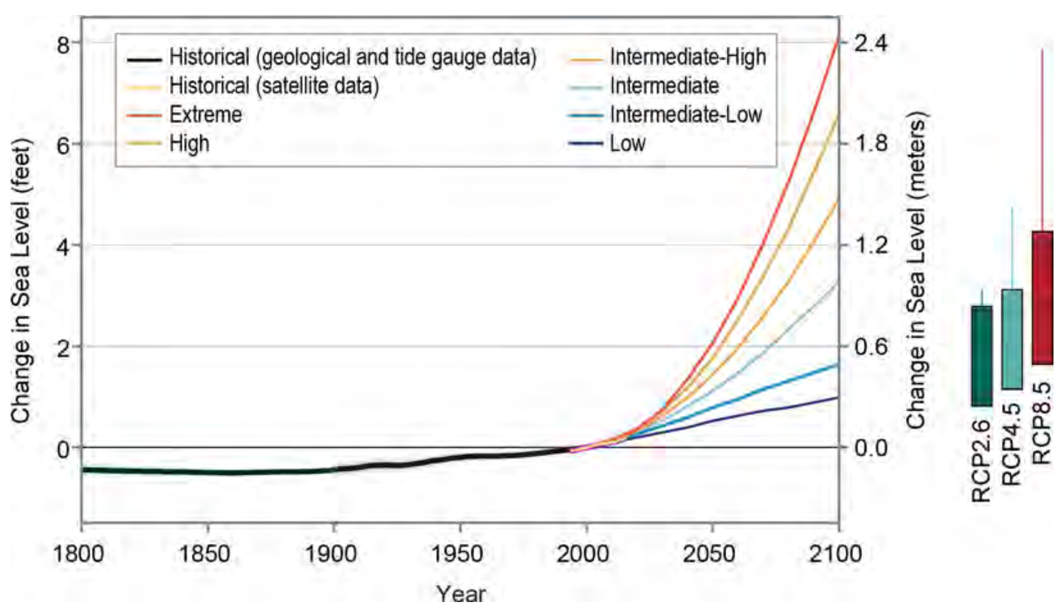

Figure 2.3. How much global average sea level will rise over the rest of this century depends on the response of the climate system to warming, as well as on future scenarios of human-caused emissions of heat-trapping gases. The colored lines show the six different global average sea level rise scenarios, 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

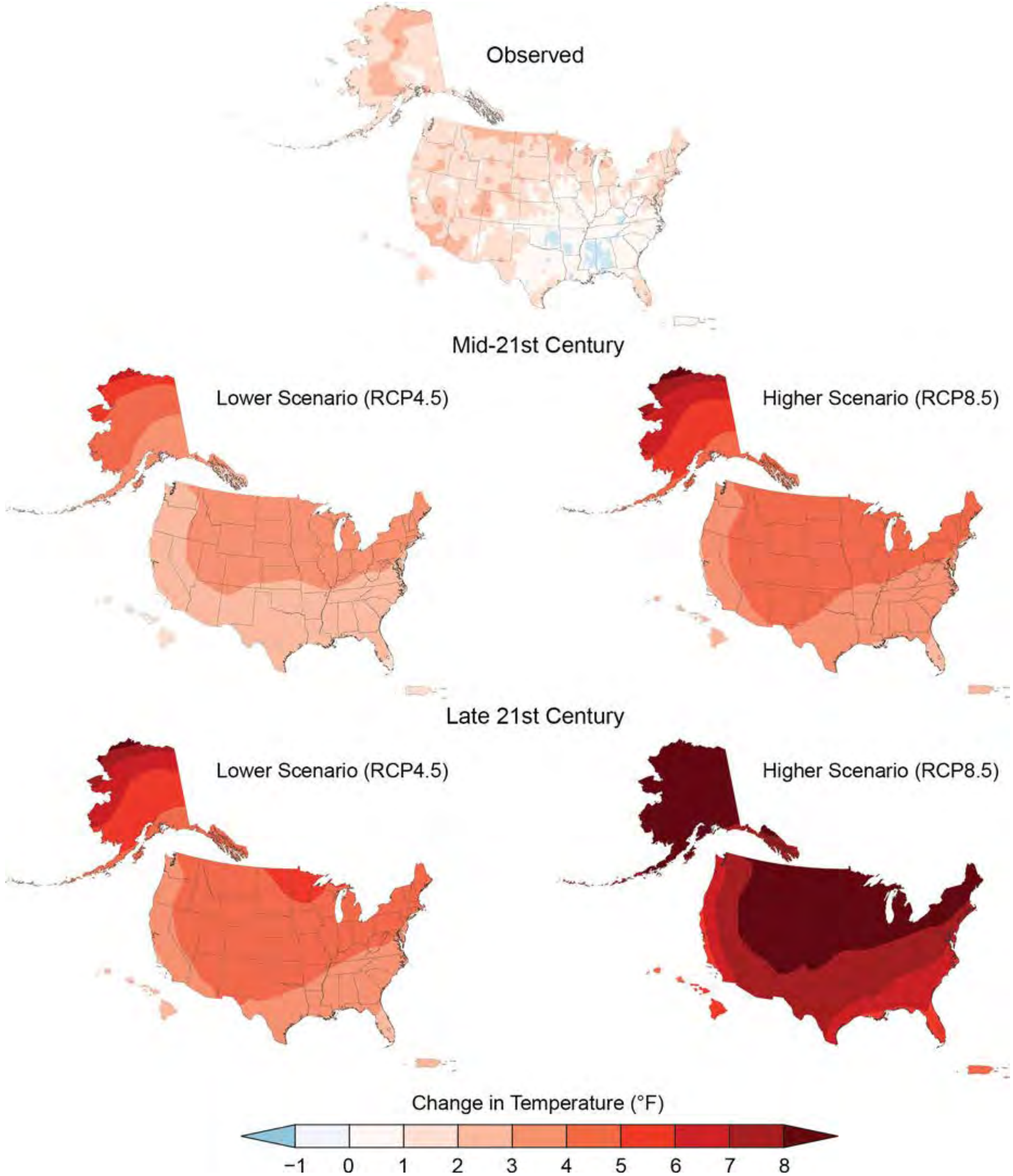

Figure 2.4: Annual average temperatures across North America are projected to increase, with proportionally greater changes at higher as compared to lower latitudes, and under a higher scenario (RCP8.5, right) as compared to a lower one (RCP4.5, left). This figure compares (top) observed change for 1986–2016 (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

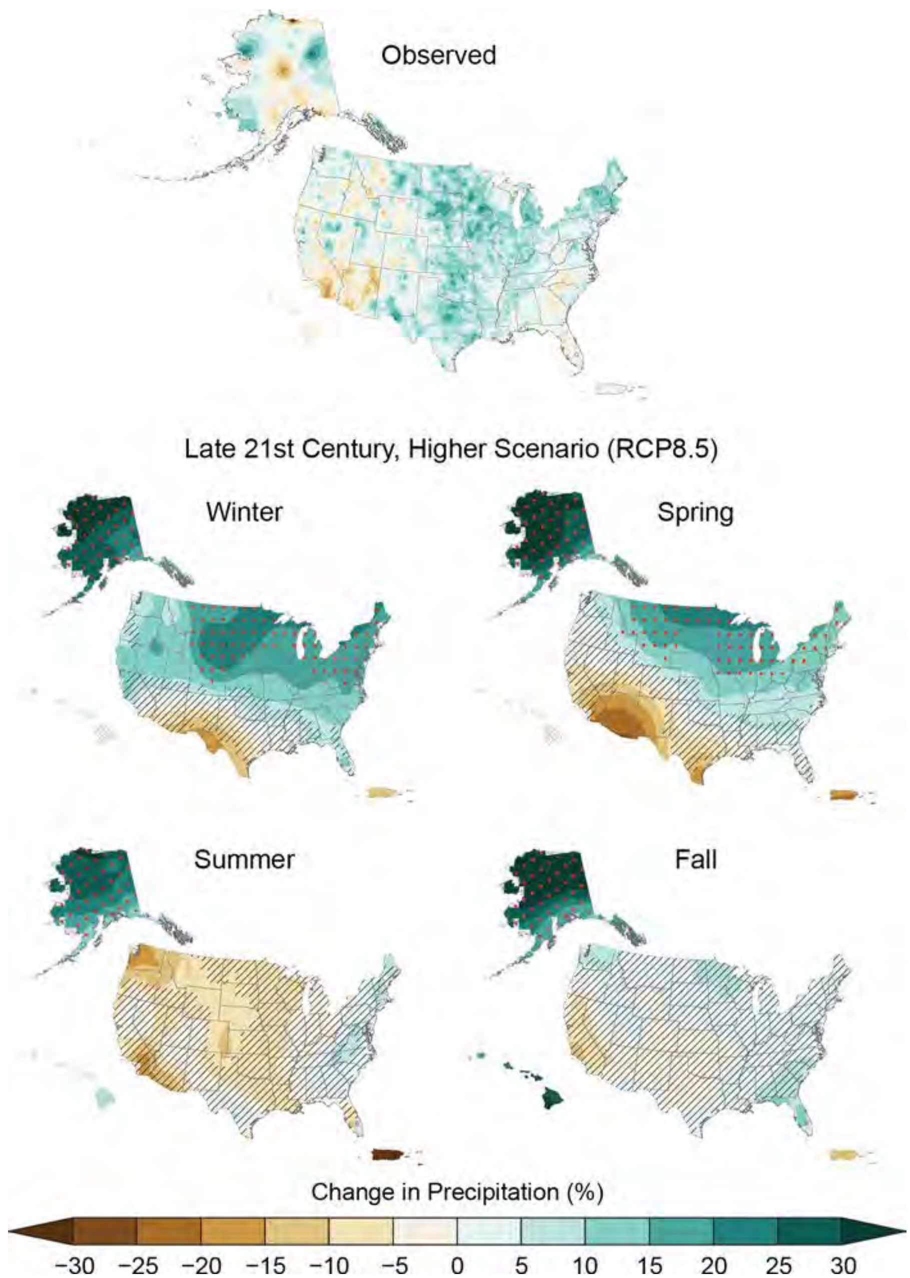

Figure 2.5: Observed and projected precipitation changes vary by region and season. (top) Historically, the Great Plains and the northeastern United States have experienced increased precipitation while the Southwest has experienced a decrease for the period 1986–2015 relative to 1901–1960. (middle and 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, Hawaiʻi, 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

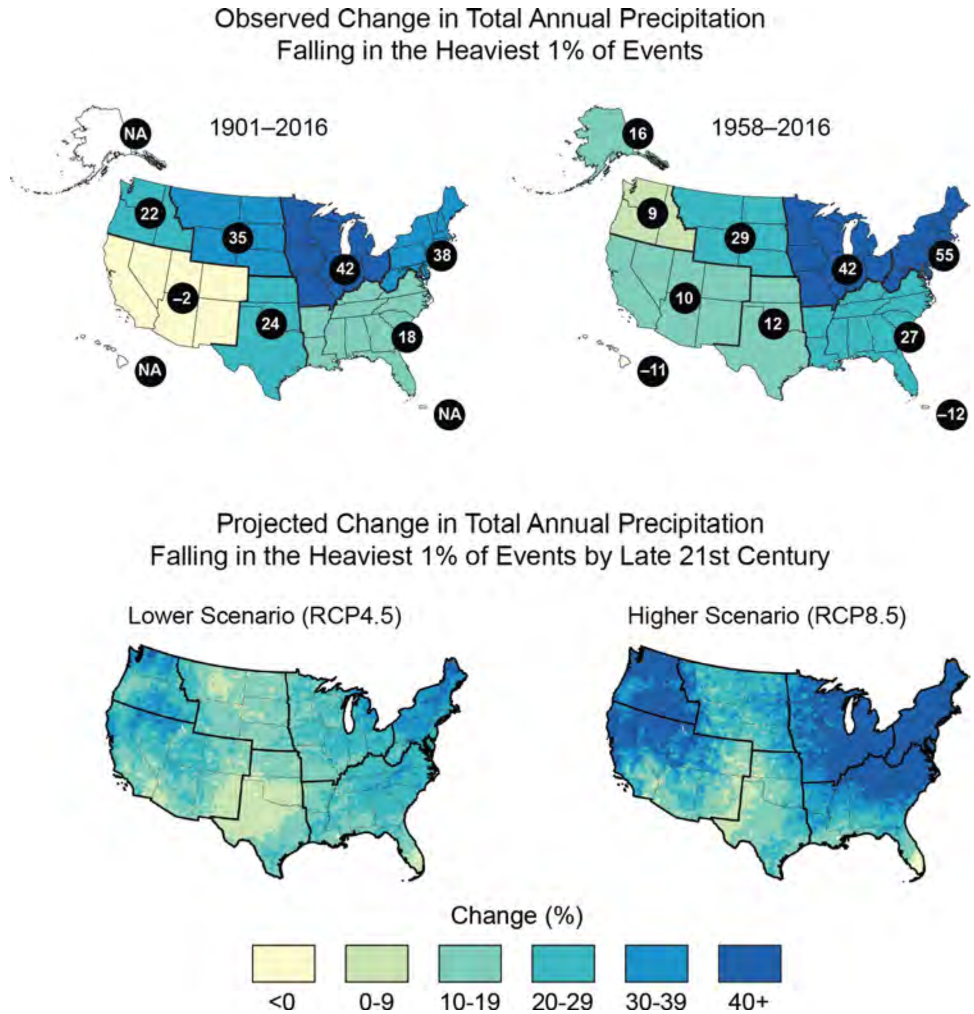

Figure 2.6: Heavy precipitation is becoming more intense and more frequent across most of the United States, particularly in the Northeast and Midwest, and these trends are projected to continue in the future. This map shows the observed (top; numbers in black circles give the percentage change) and 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

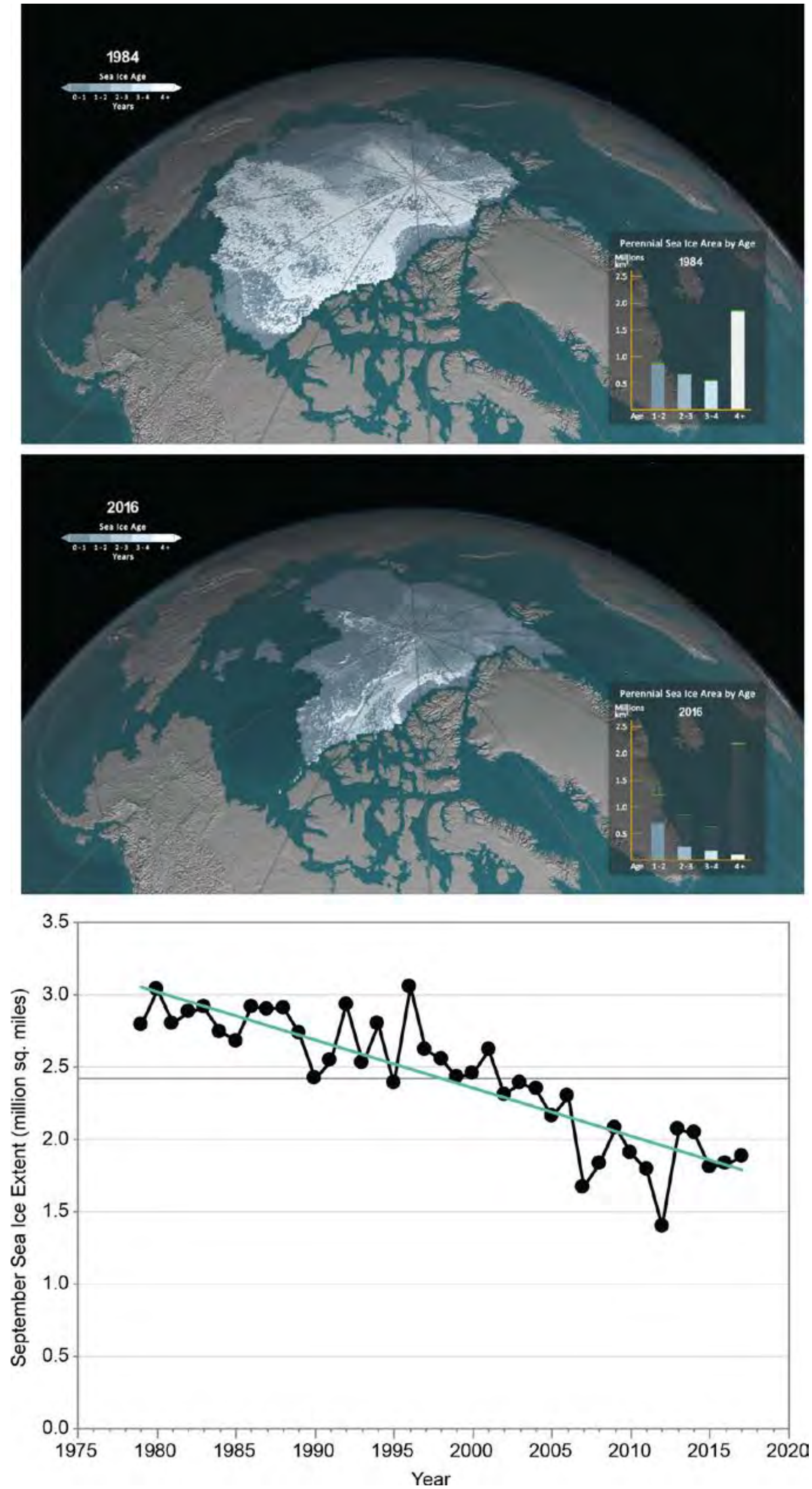

Figure 2.7: As the Arctic warms, sea ice is shrinking and becoming thinner and younger. The top and middle panels show how the summer minimum ice extent and average age, measured in September of each year, changed from 1984 (top) to 2016 (middle). An animation of the complete time series is available 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

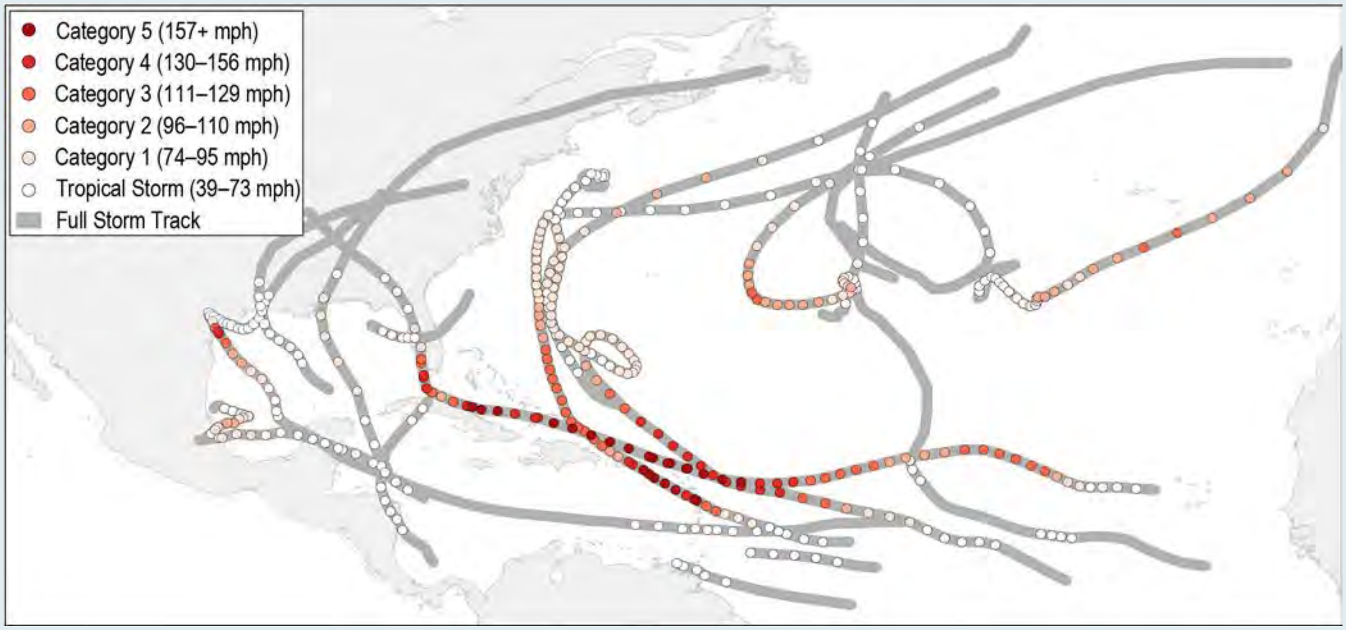

Figure 2.8: Tropical cyclone tracks for the 2017 Atlantic hurricane season. Data are based on the preliminary "operational best-track" provided by the NOAA National Hurricane Center and may change slightly after post-season reanalysis is completed. Sources: NOAA NCEI and ERT, Inc.

Notable 2017 Hurricanes

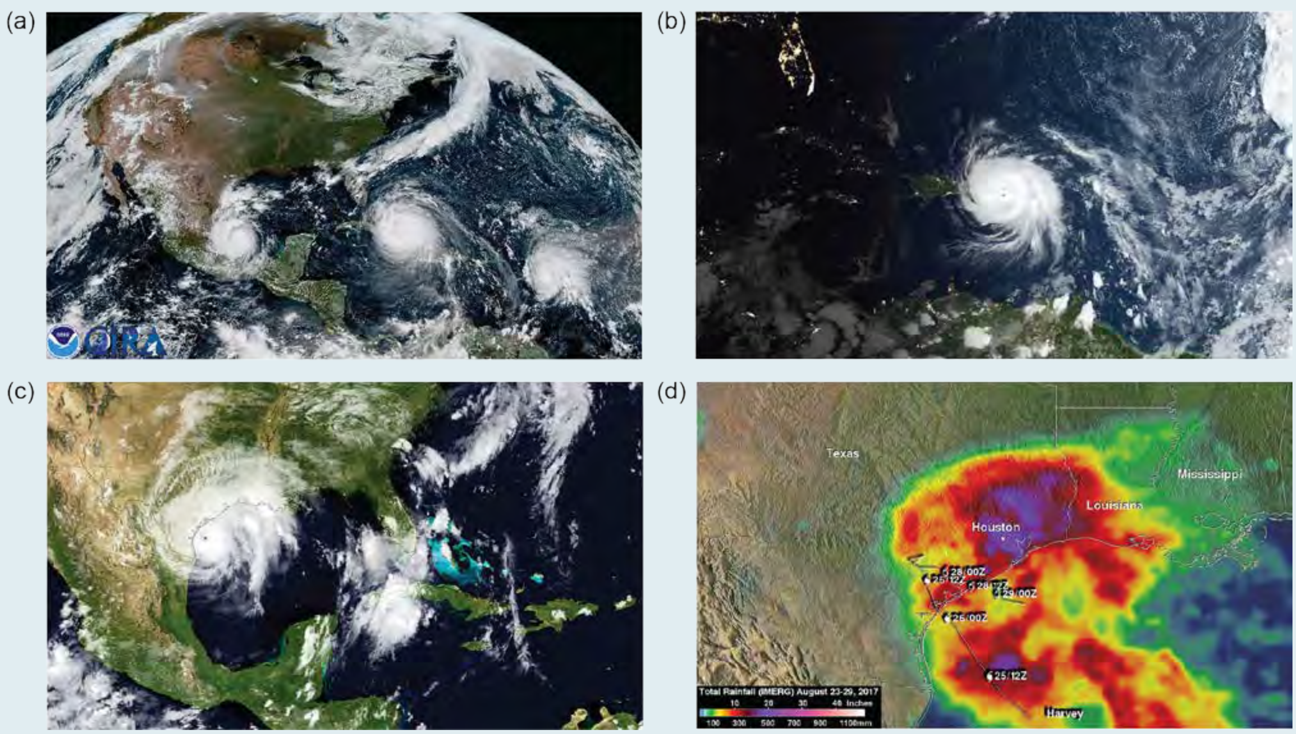

Figure 2.9: (a) Visible imagery from the GOES satellite shows Hurricanes Katia (west), Irma (center) and Jose (east) stretched across the Atlantic on September 8, 2017; (b) Hurricane Maria about to make landfall over Puerto Rico on September 19, 2017; (c) Hurricane Harvey making landfall in Texas on 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*

Scientific Understanding of Global Climate

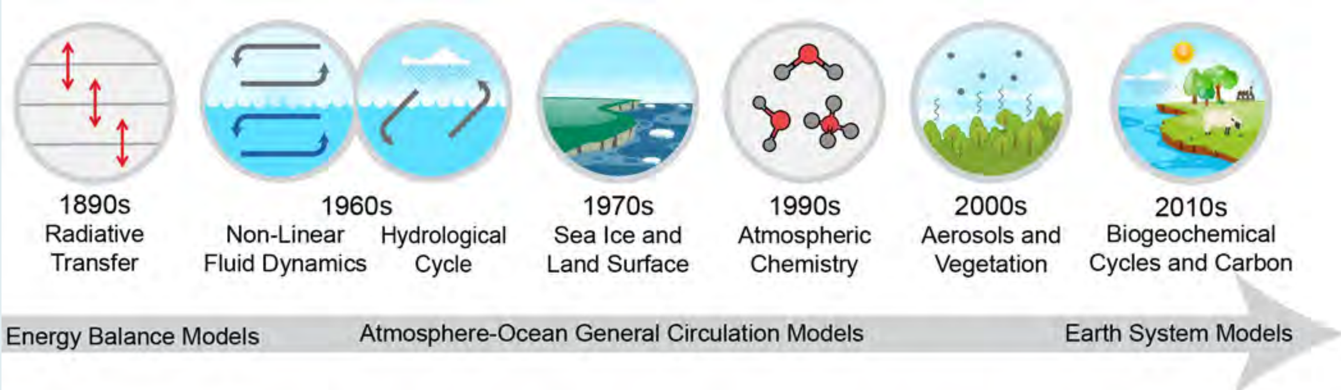

Figure 2.10: As scientific understanding of climate has evolved over the last 120 years, increasing amounts of physics, chemistry, and biology have been incorporated into calculations and, eventually, models. This figure shows when various processes and components of the climate system became regularly 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 ver*y 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 1.2ºF (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 downscaling 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 0.08ºC to 0.50ºC 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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Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

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Recommended Citation for Chapter

Lall, U., T. Johnson, P. Colohan, A. Aghakouchak, C. Brown, G. McCabe, R. Pulwarty, and A. Sankarasubramanian, 2018: Water. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 136–164. doi: 10.7930/NCA4.2018.CH3

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

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.

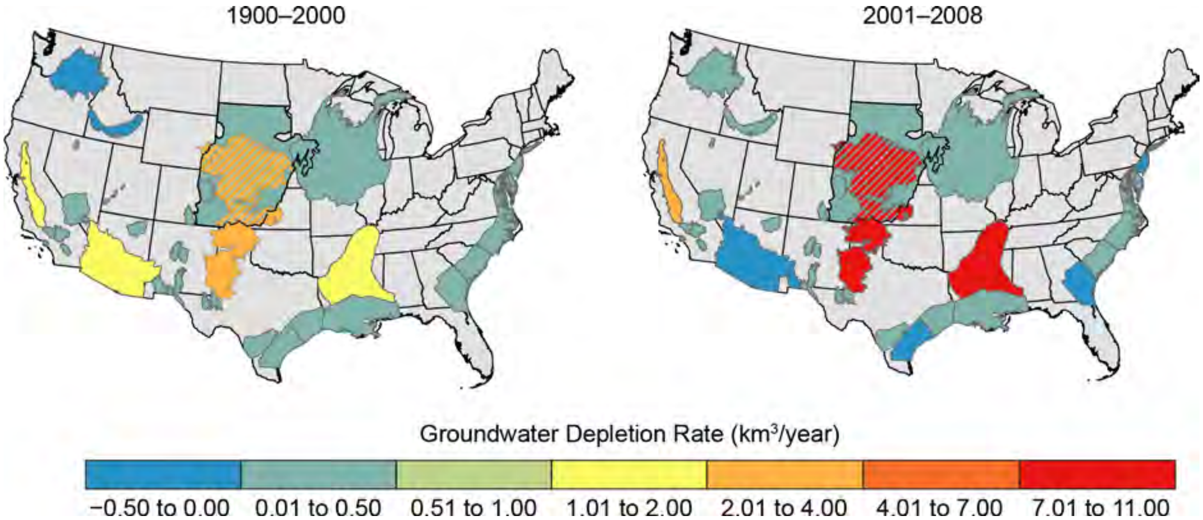
Executive Summary

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

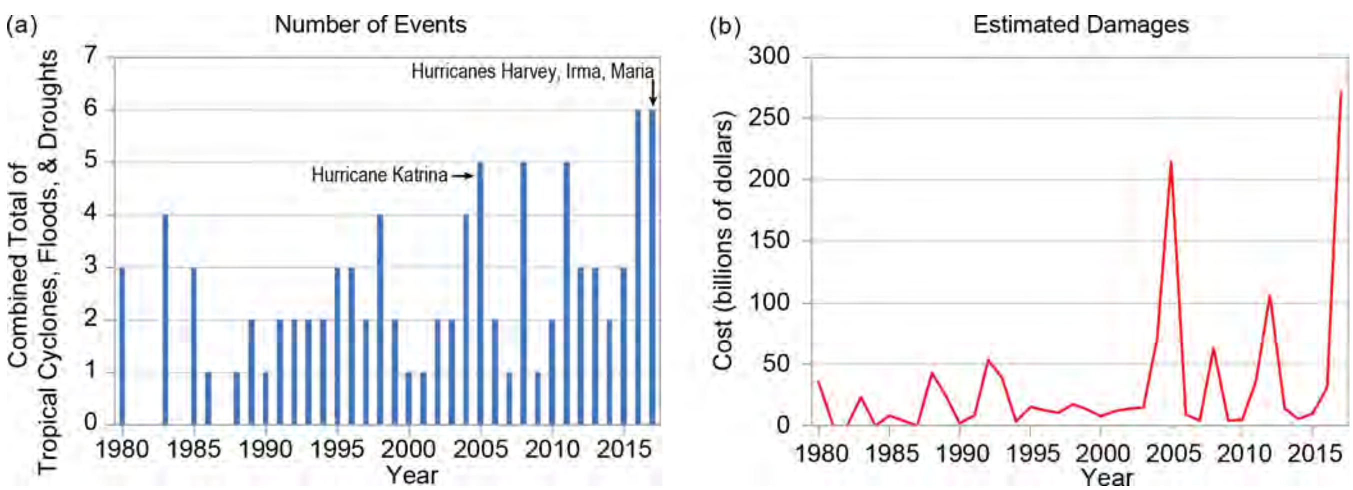


Figure 3.1: The figure shows (a) the total number of water-related billion-dollar disaster events (tropical cyclones, flooding, and droughts combined) each year in the United States and (b) the associated costs (in 2017 dollars, adjusted for inflation). Source: adapted from NOAA NCEI 2018.[19]

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

Depletion of Groundwater in Major U.S. Regional Aquifers

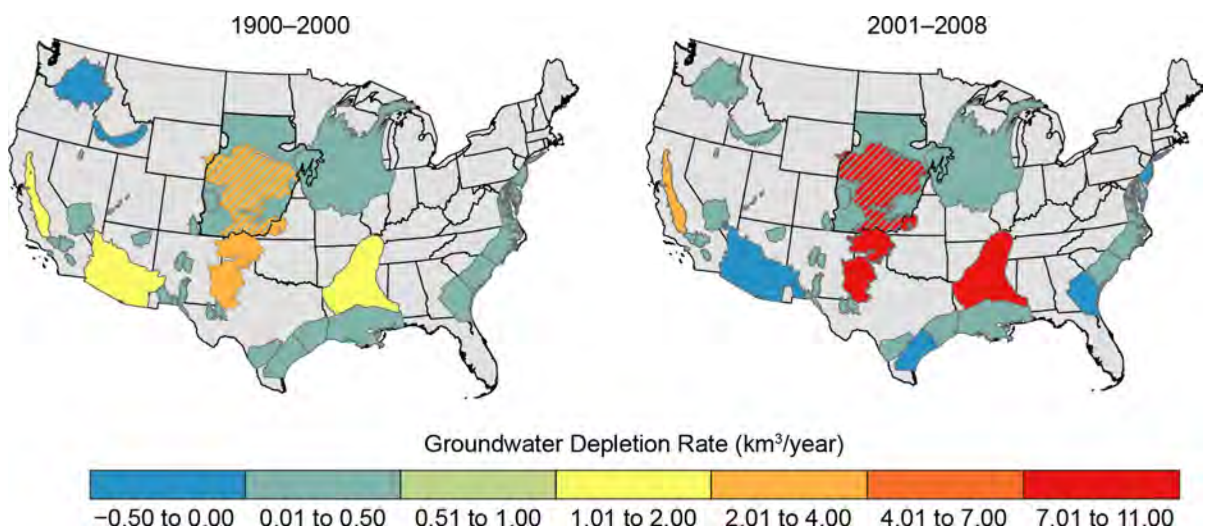


Figure 3.2: (left) Groundwater supplies have been decreasing in the major regional aquifers of the United States over the last century (1900–2000). (right) This decline has accelerated recently (2001–2008) due to persistent droughts in many regions and the lack of adequate surface water storage to meet 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

Colorado River Basin Supply and Use

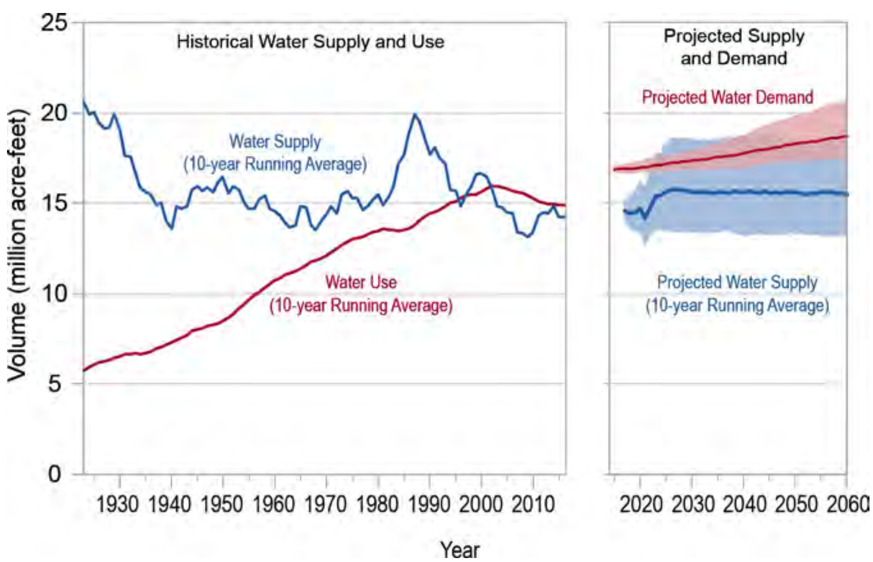


Figure 3.3: The figure shows the Colorado River Basin historical water supply and use, along with projected water supply and demand. The figure illustrates a challenge faced by water managers in many U.S. locations—a potential imbalance between future supply and demand but with considerable long-term 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]

Acknowledgments

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Opening Image Credit

Levee repair: U.S. Army Corps of Engineers, Sacramento District.

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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Recommended Citation for Chapter

Zamuda, C., D.E. Bilello, G. Conzelmann, E. Mecray, A. Satsangi, V. Tidwell, and B.J. Walker, 2018: Energy Supply, Delivery, and Demand. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 165–192. doi: 10.7930/NCA4.2018.CH4

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

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

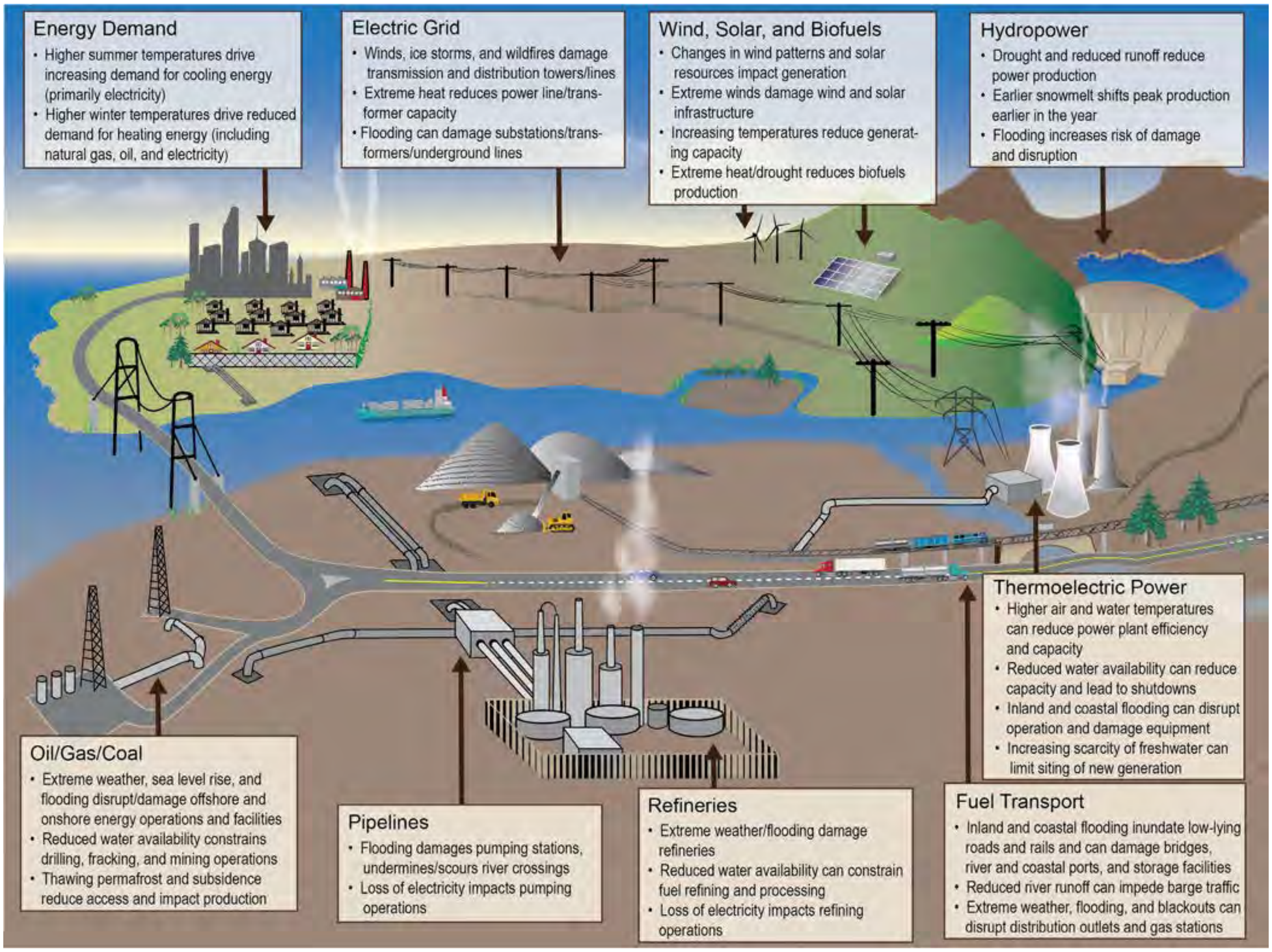
The Nation's economic security is increasingly dependent on an affordable and reliable supply of energy.[1,2] Every sector of the economy depends on energy, from manufacturing to agriculture, banking, healthcare, telecommunications, and transportation. Increasingly, climate change and extreme weather 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

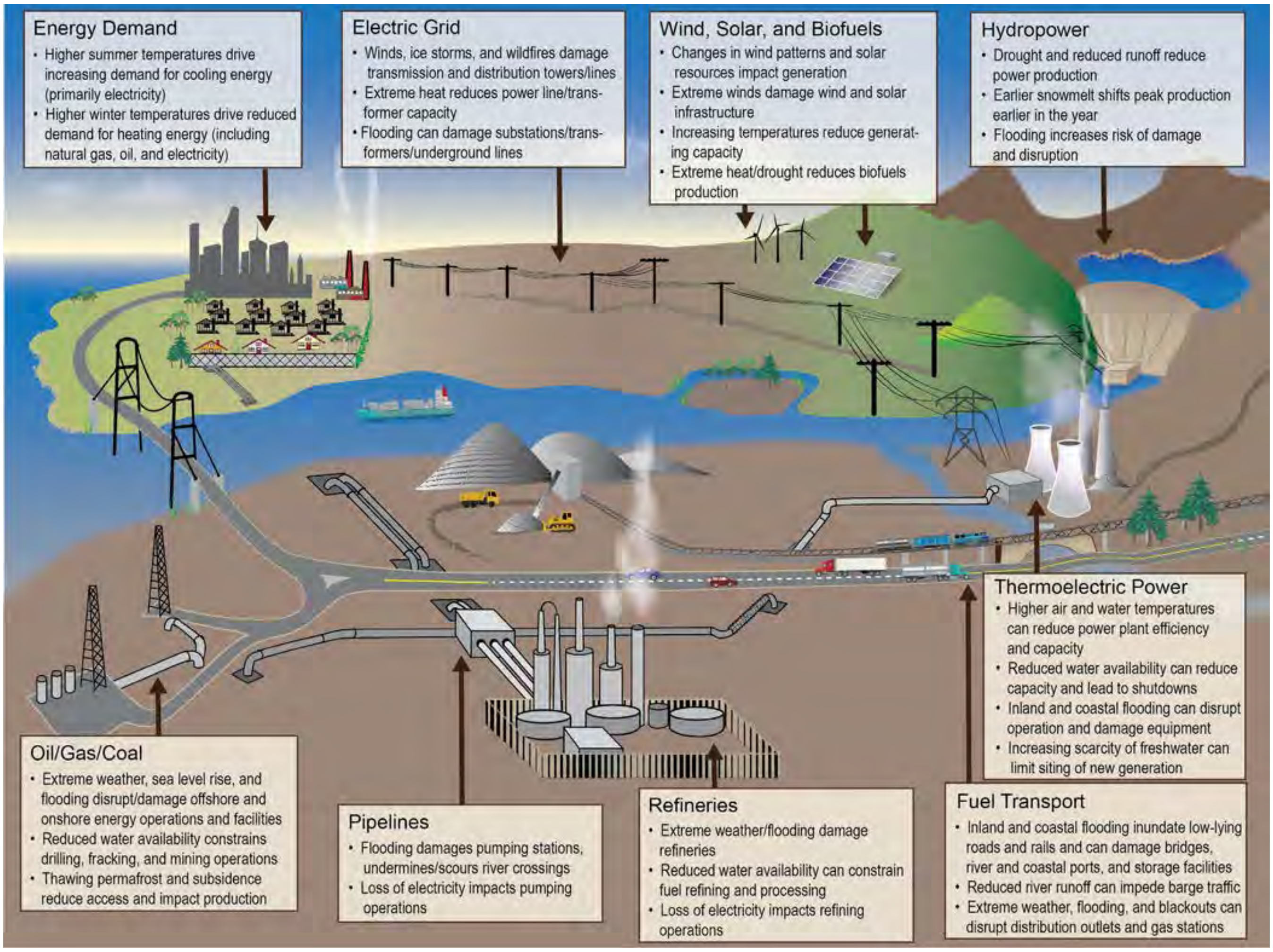


Figure 4.1: Extreme weather and climate change can potentially impact all components of the Nation's energy system, from fuel (petroleum, coal, and natural gas) production and distribution to electricity generation, transmission, and demand. Source: adapted from DOE 2013.[23]

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

Projected Changes in Energy Expenditures

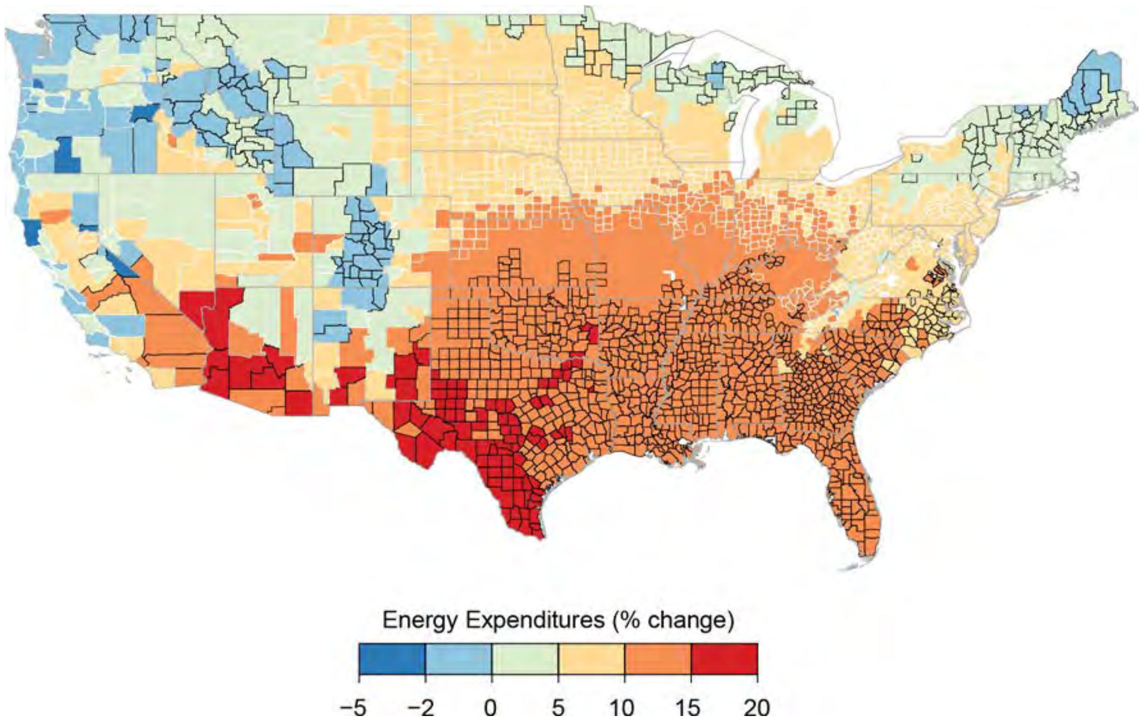


Figure 4.2: This figure shows county-level median projected increases in energy expenditures for average 2080–2099 impacts under the higher scenario (RCP8.5). Impacts are changes relative to no additional change in climate. Color indicates the magnitude of increases in energy expenditures in median projection; 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

Electricity Generation from Selected Fuels

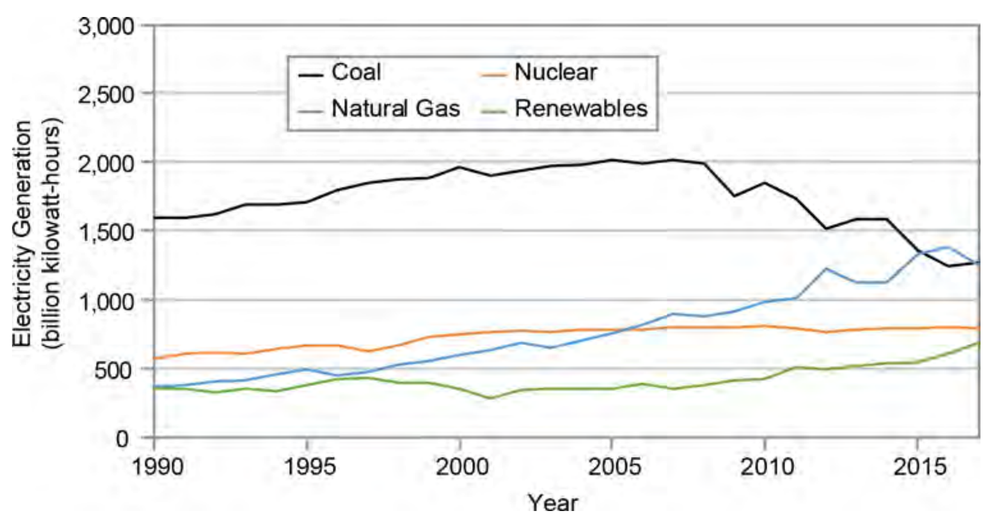


Figure 4.3: This figure shows electric power generation from different fuel sources and technologies. Since 2010, the declining market share from coal has been filled largely by natural gas and, to a lesser extent, renewables. Renewables include: conventional hydroelectric, geothermal, wood, wood waste, 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

Examples of Critical Infrastructure Interdependencies

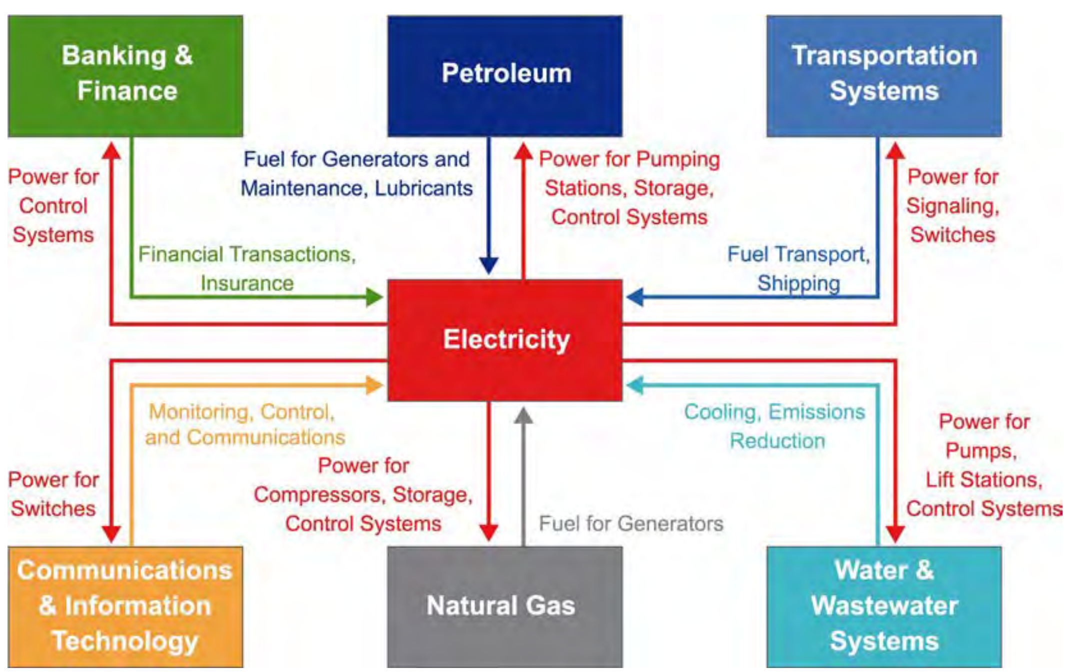


Figure 4.4: The interdependence of critical infrastructure systems increases the importance of electricity resilience, as disruptions to energy services are projected to affect other sectors. Shown above is a representative set of connections, and the complex relationships are analogous to other systems (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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Recommended Citation for Chapter

Sleeter, B.M., T. Loveland, G. Domke, N. Herold, J. Wickham, and N. Wood, 2018: Land Cover and Land-Use Change. In I*mpacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 193–222. doi: 10.7930/NCA4.2018.CH5

On the Web: https://nca2018.globalchange.gov/chapter/land-changes

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

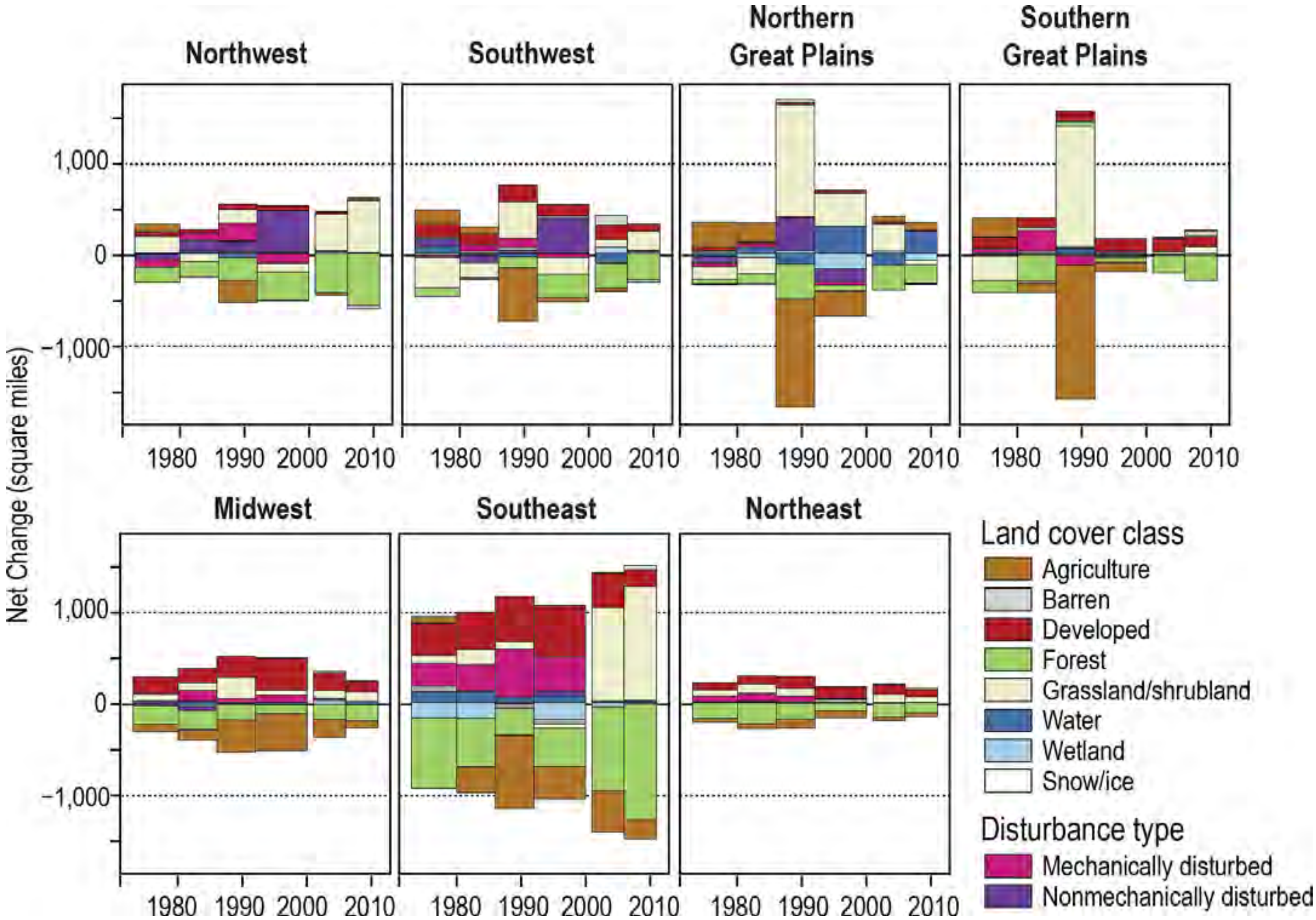
Climate can affect and be affected by changes in land cover (the physical features that cover the land such as trees or pavement) and land use (human management and activities on land, such as mining or recreation). A forest, for instance, would likely include tree cover but could also include areas 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, KM1).

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

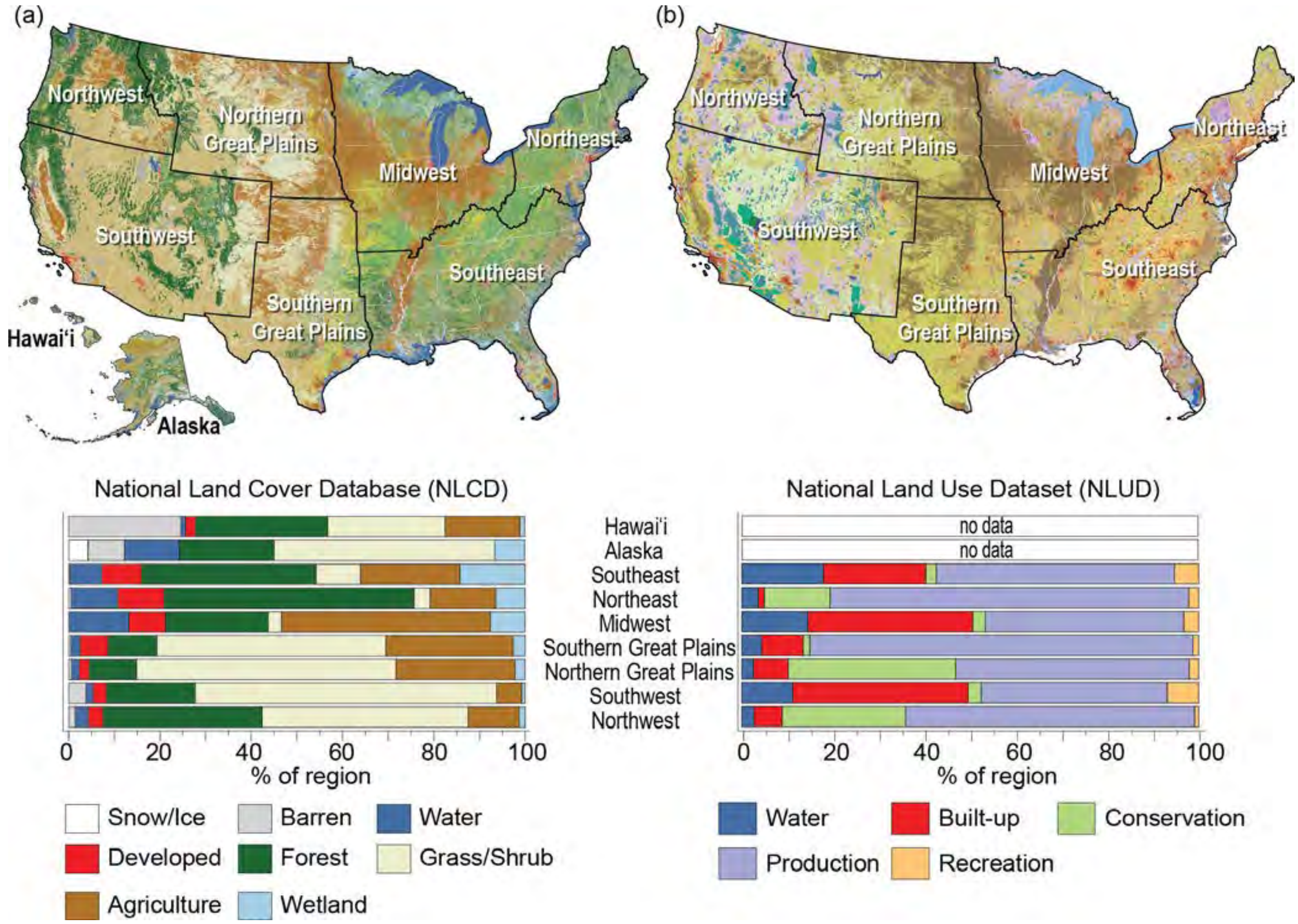


Figure 5.1: The composition of land use and land cover (LULC) is highly variable across the United States, owing in part to the natural environmental settings of each region. Forests dominate much of the vegetated areas of the eastern United States, while much of the Great Plains and Southwest are dominated 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

Changes in Land Cover by Region

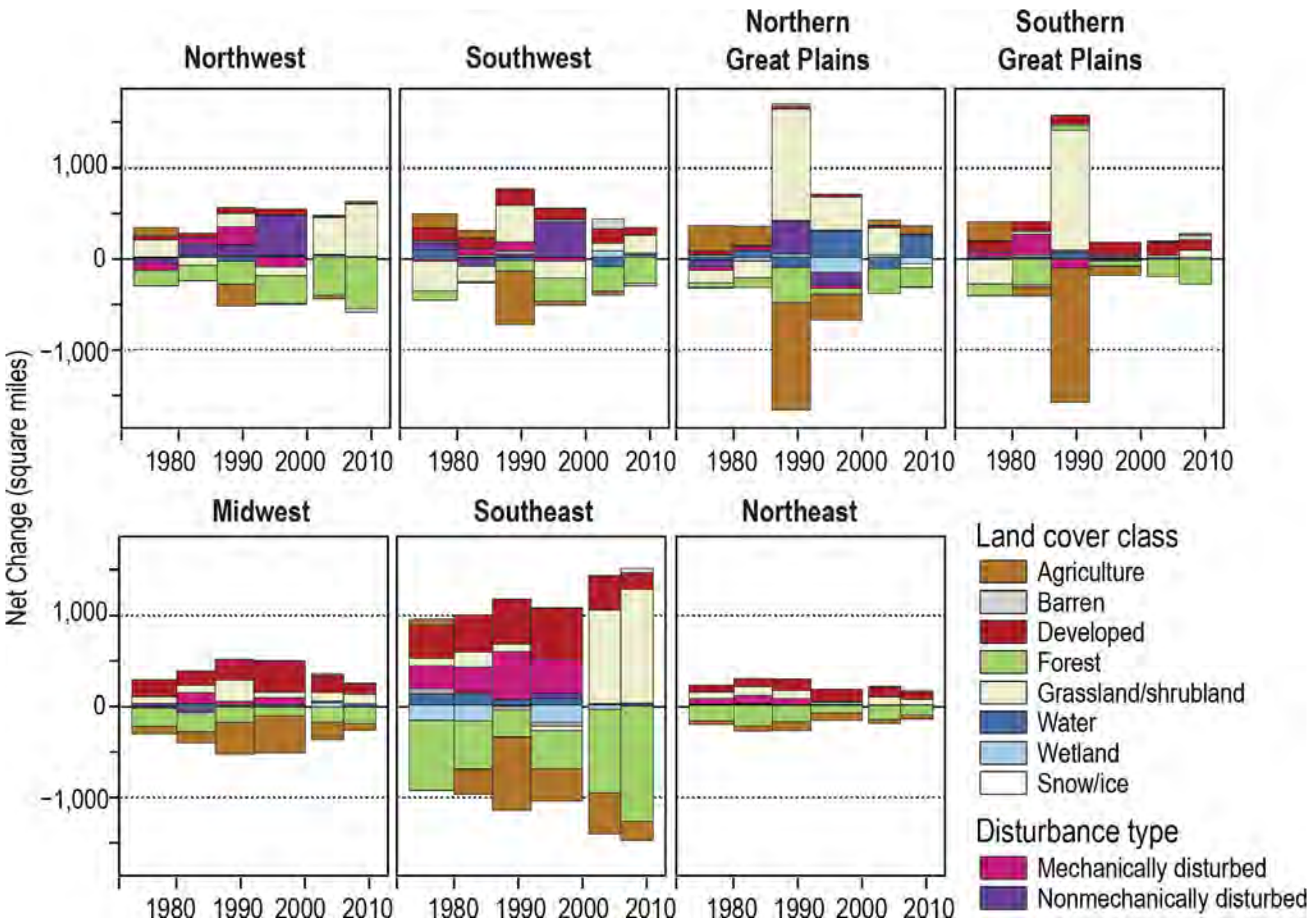


Figure 5.2: The figure shows the net change in land cover by class in square miles, from 1973 to 2011. Land-cover change has been highly dynamic over space, time, and sector, in response to a range of driving forces. Net change in land cover reveals the trajectory of a class over time. A dramatic example 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

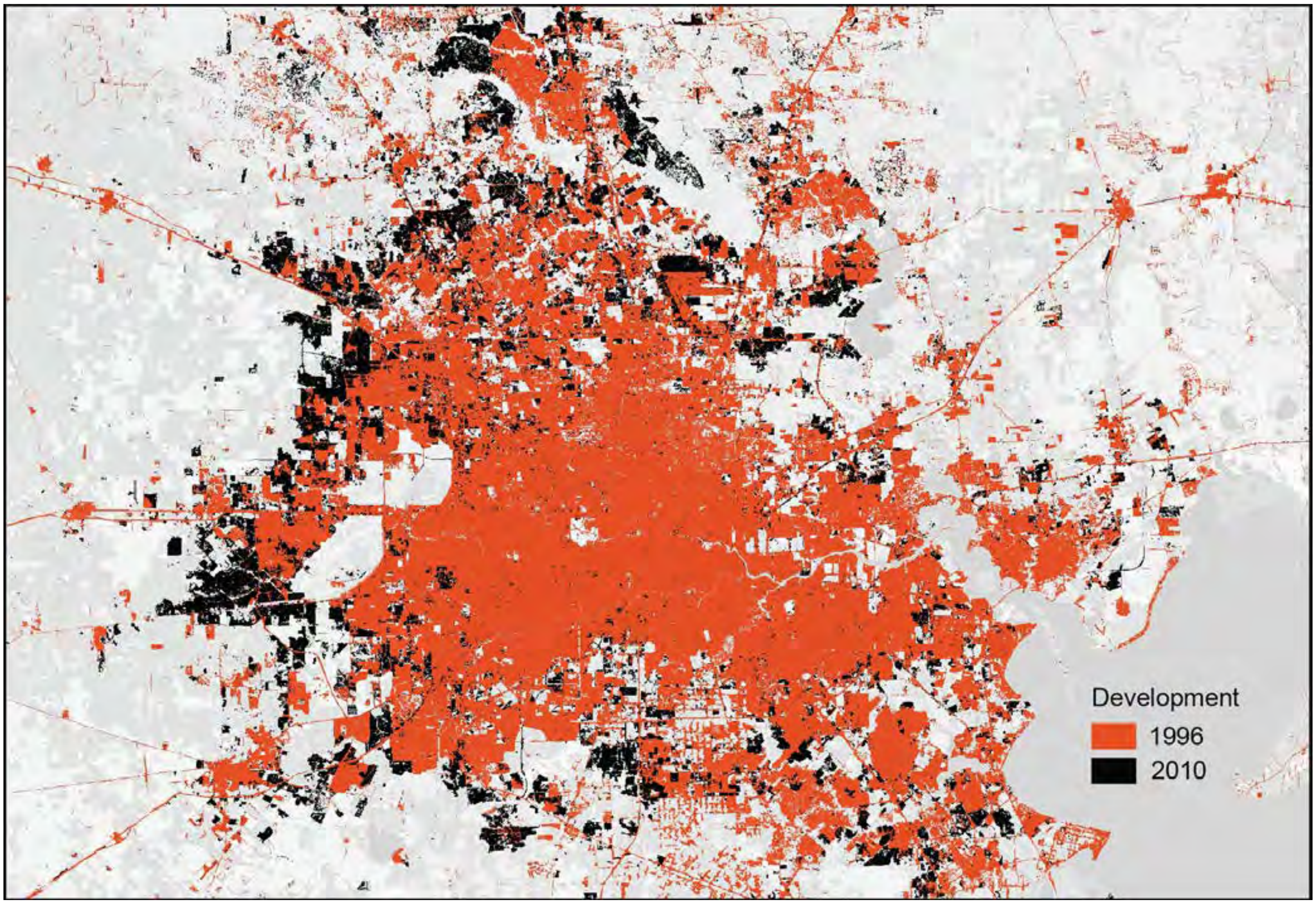


Figure 5.3: The figure shows the development-related changes surrounding Houston, Texas, from 1996 to 2010, as mapped by NOAA's Coastal Change and Analysis Program (C-CAP). Areas of change between 1996 and 2010 are shown in black.[63] These changes can have numerous impacts on the environment and populations, 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 Hawaiʻi 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 agrono- my-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]

Acknowledgments

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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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Recommended Citation for Chapter

Vose, J.M., D.L. Peterson, G.M. Domke, C.J. Fettig, L.A. Joyce, R.E. Keane, C.H. Luce, J.P. Prestemon, L.E. Band, J.S. Clark, N.E. Cooley, A. D'Amato, and J.E. Halofsky, 2018: Forests. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 223–258. doi: 10.7930/NCA4.2018.CH6

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

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]

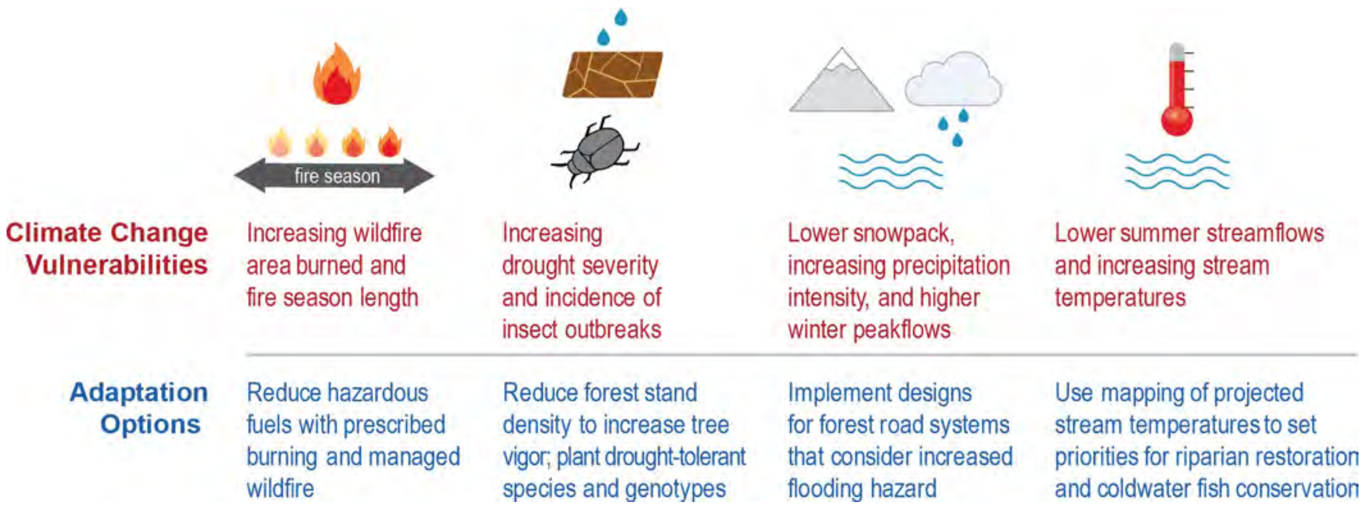
A warmer climate will decrease tree growth in most forests that are water limited (for example, low-elevation ponderosa pine forests) but will likely increase growth in forests that are energy limited (for example, subalpine forests, where long-lasting snowpack and cold temperatures limit the growing 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



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 Hawaiʻi. 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: Hawaiʻi & 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.

Climate Change Effects on Ecosystem Services

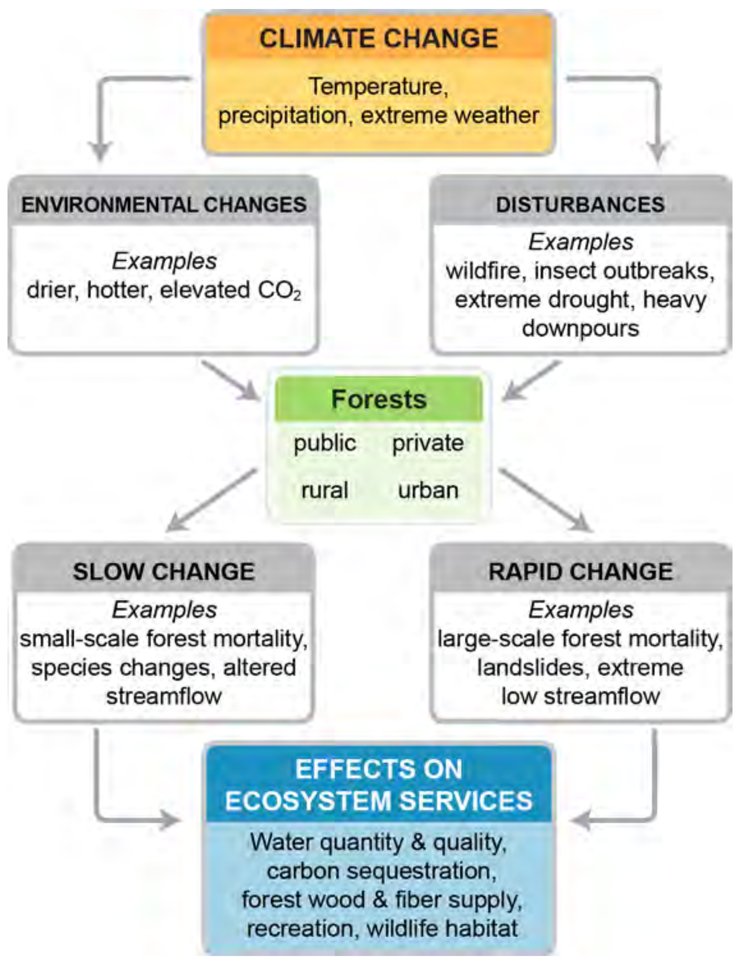


Figure 6.1: Many factors in the biophysical environment interact with climate change to influence forest productivity, structure, and function, ultimately affecting the ecosystem services that forests provide to people in the United States and globally. Source: U.S. Forest Service.

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

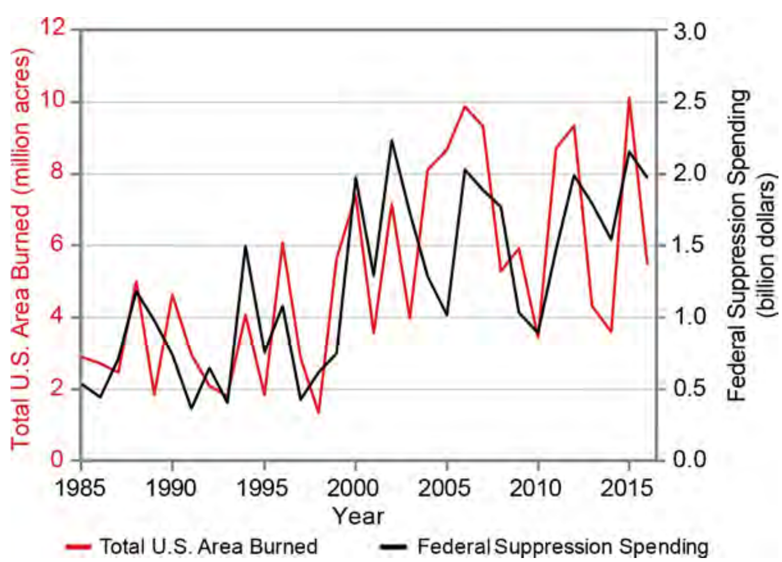


Figure 6.4: This figure shows the annual wildfire area burned in the United States (red) and the annual federal wildfire suppression expenditures (black), scaled to constant 2016 U.S. dollars (Consumer Price Index deflated). Trends for both area burned and wildfire suppression costs indicate about a 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]

Area Burned by Large Wildfires

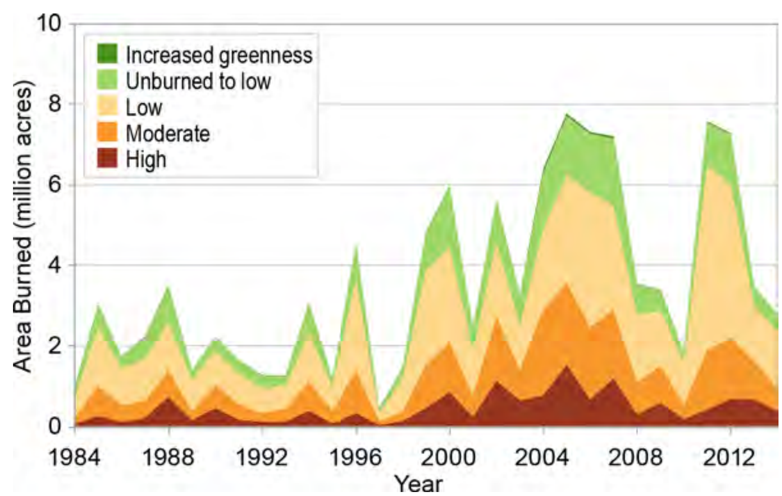


Figure 6.5: This figure illustrates the area burned by large wildfires (greater than 1,000 acres in the western United States and greater than 500 acres in the eastern United States) for 1984–2014. Although the area with moderate-to-high burn severity (amount of fire damage to the forest canopy) has 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

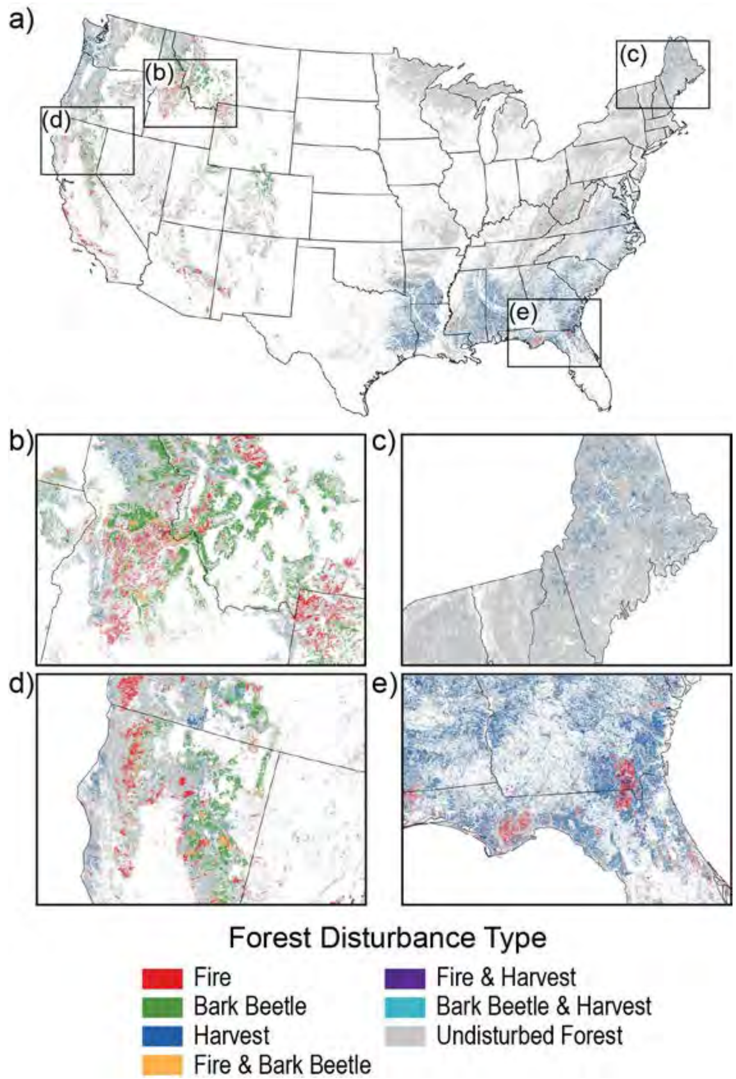


Figure 6.6: This figure shows the cumulative area of disturbed forestland across the contiguous United States for 1984–2014. The small boxes illustrate how disturbances differ regionally. Data for Alaska, Hawai‘i and the U.S.-Affiliated Pacific Islands, and the U.S. Caribbean regions were not shown on 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

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

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 coldwater 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.

Acknowledgments

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Opening Image Credit

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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Recommended Citation for Chapter

Lipton, D., M.A. Rubenstein, S.R. Weiskopf, S. Carter, J. Peterson, L. Crozier, M. Fogarty, S. Gaichas, K.J.W. Hyde, T.L. Morelli, J. Morisette, H. Moustahfid, R. Muñoz, R. Poudel, M.D. Staudinger, C. Stock, L. Thompson, R. Waples, and J.F. Weltzin, 2018: Ecosystems, Ecosystem Services, and Biodiversity. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 259–312. doi: 10.7930/NCA4.2018.CH7

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

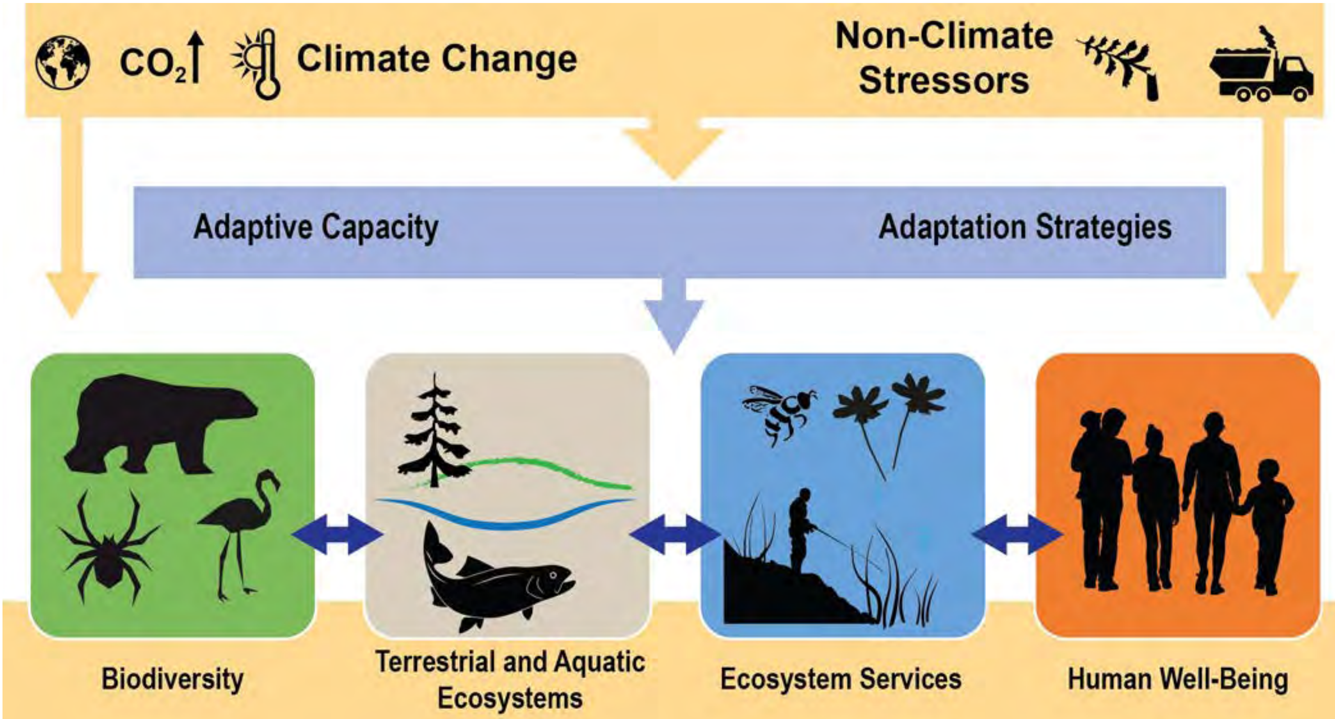
Traditional natural resource management strategies are increasingly challenged by the impacts of climate change. Adaptation strategies that are flexible, consider interacting impacts of climate and other stressors, and are coordinated across landscape scales are progressing from theory to application. 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]

Climate Change, Ecosystems, and Ecosystem Services

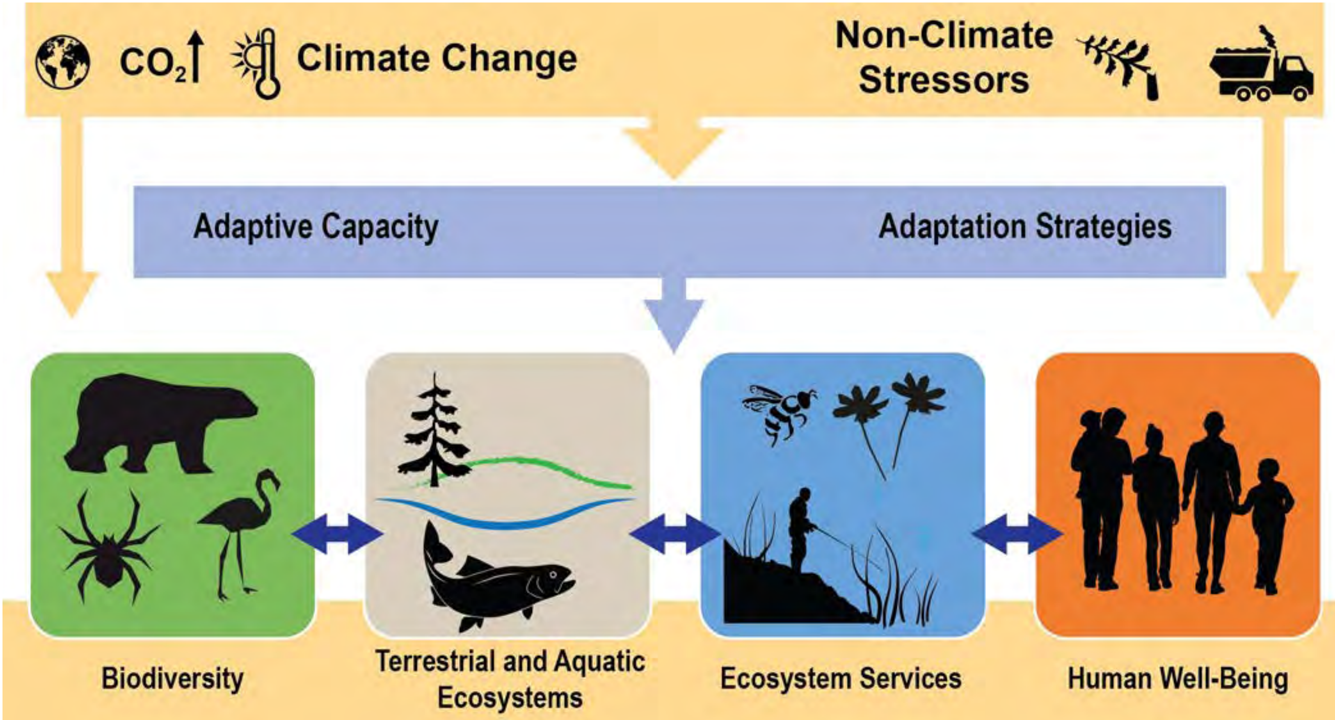


Figure 7.1: Climate and non-climate stressors interact synergistically on biological diversity, ecosystems, and the services they provide for human well-being. The impact of these stressors can be reduced through the ability of organisms to adapt to changes in their environment, as well as through adaptive 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]

Genetic Diversity and Climate Exposure

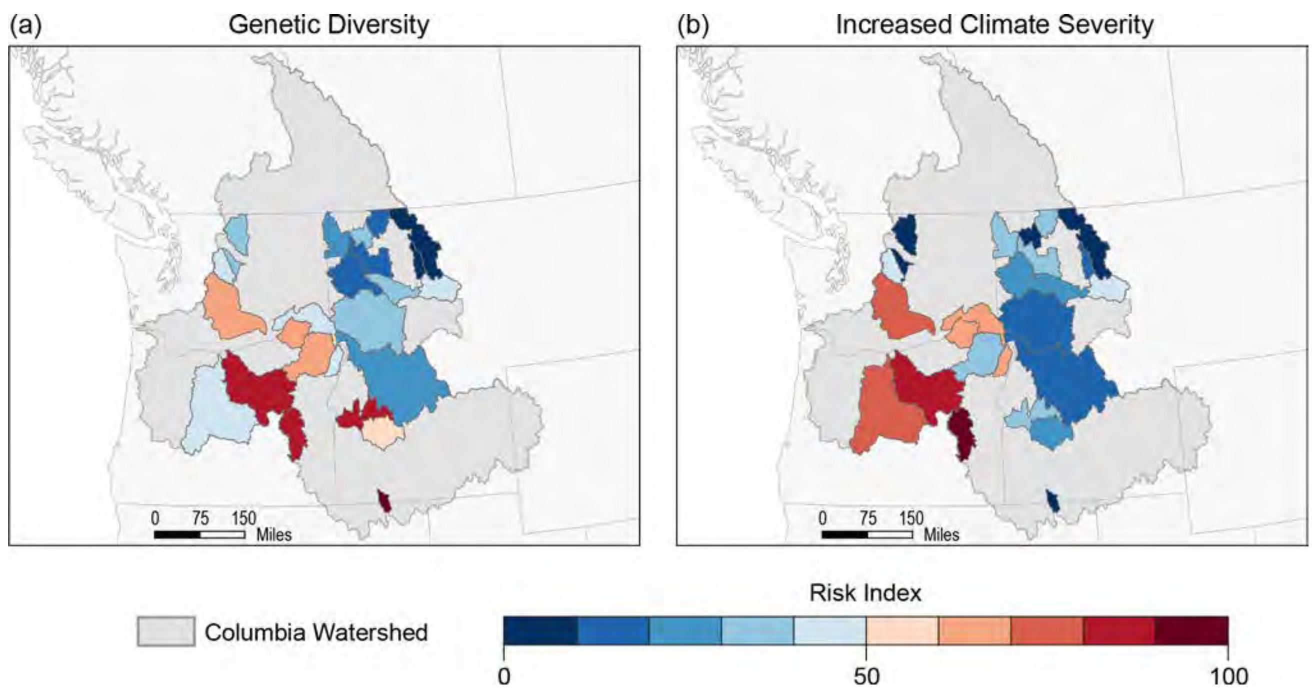


Figure 7.2: Genetic diversity is the fundamental basis of adaptive capacity. Throughout the Pacific Northwest, (a) bull trout genetic diversity is lowest in the same areas where (b) climate exposure is highest; in this case, climate exposure is a combination of maximum temperature and winter flood risk. 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

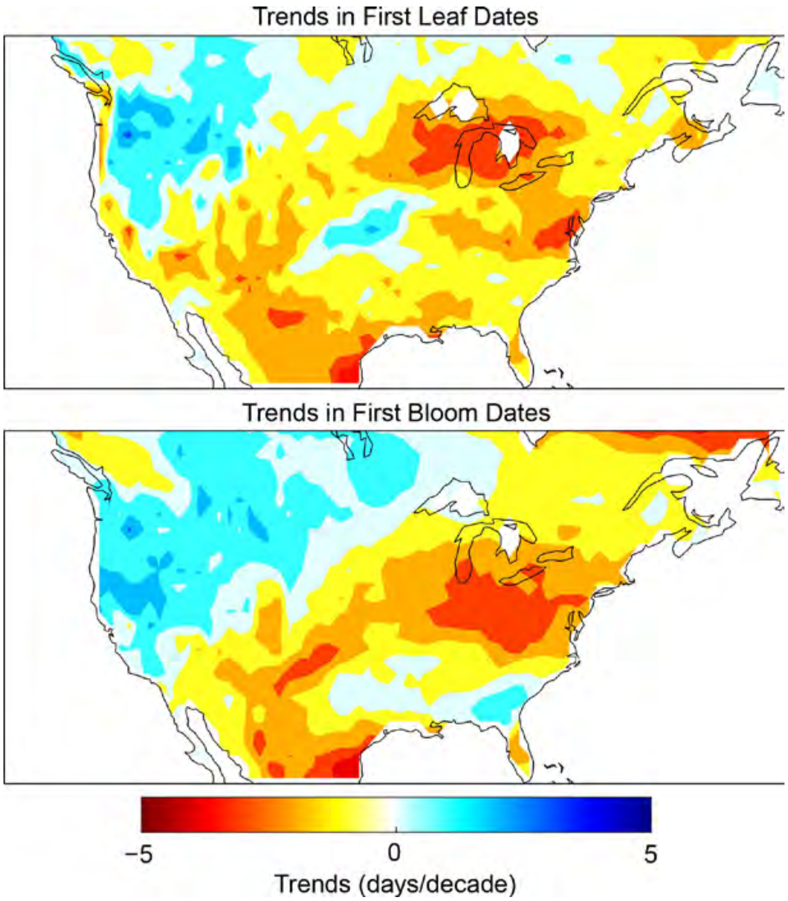


Figure 7.3: These maps show observed changes in timing of the start of spring over the period 1981–2010, as represented by (top) an index of first leaf date (the average date when leaves first appear on three indicator plants) and (bottom) an index of first bloom date (the average date when blossoms 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

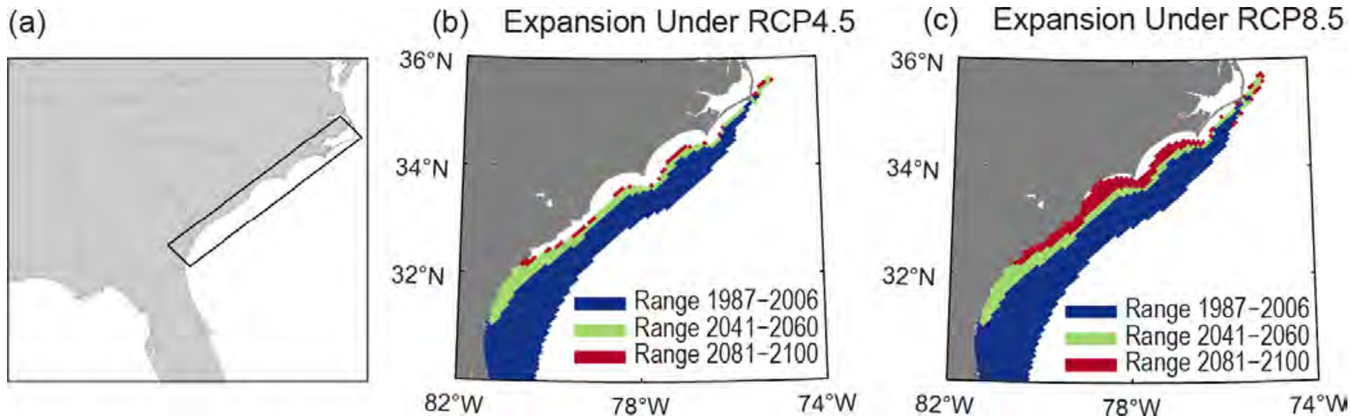


Figure 7.4: Lionfish, native to the Pacific Ocean, are an invasive species in the Atlantic. Their range is projected to expand closer to (a) the U.S. Atlantic coastline as a result of climate change. The maps show projected range expansion of the invasive lionfish in the southeast United States by mid-century (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.

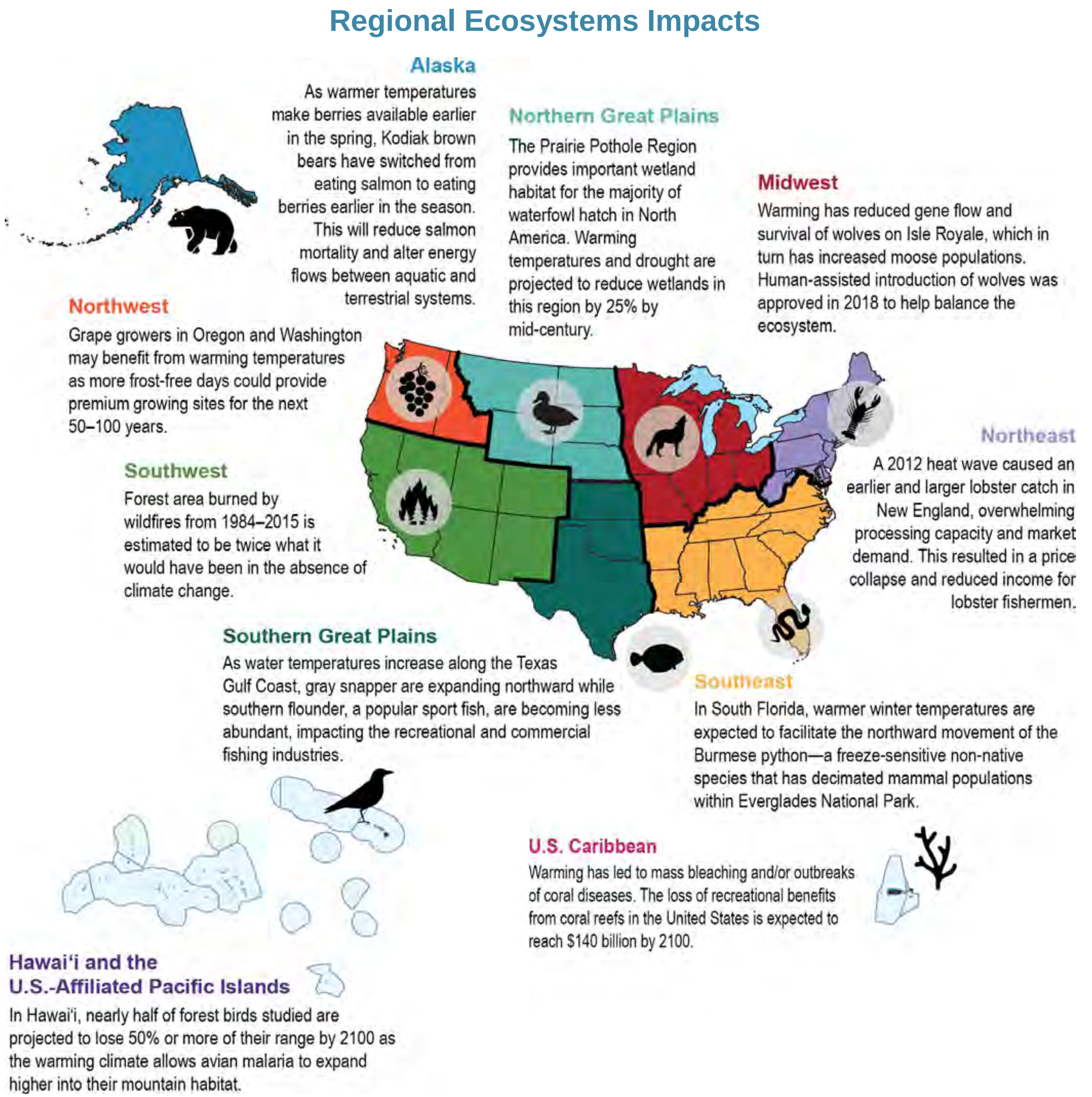


Figure 7.5: This figure shows selected examples of impacts to biodiversity, ecosystems, and ecosystem services that are linked to climate change throughout the United States. See the online version at https://nca2018.globalchange.gov/chapter/7#fig-7-5 for more examples and references. Source: adapted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

Agricultural Productivity

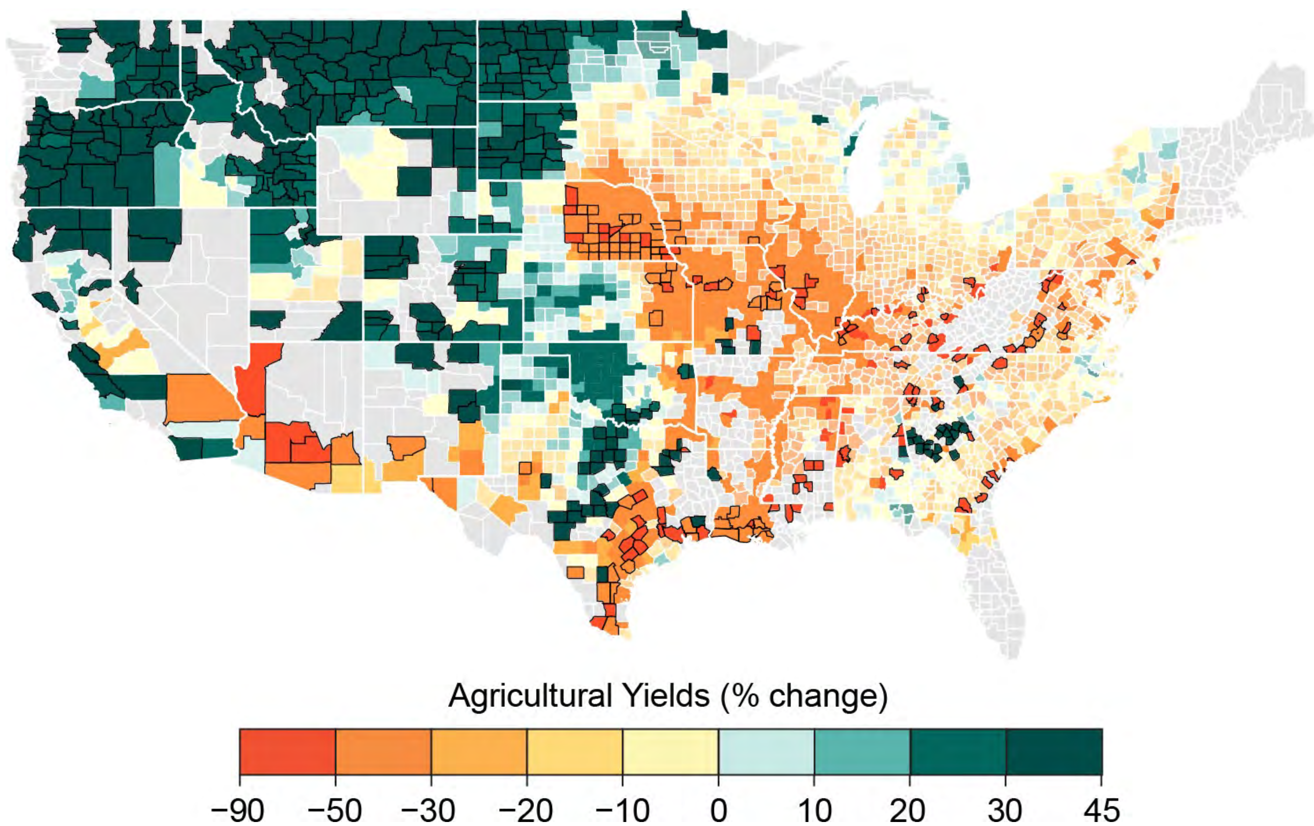


Figure 7.6: The figure shows the projected percent change in the yield of corn, wheat, soybeans, and cotton during the period 2080–2099. Units represent average percent change in yields under the higher scenario (RCP8.5) as compared to a scenario of no additional climate change. Warmer colors (negative 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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Recommended Citation for Chapter
Fleming, E., J. Payne, W. Sweet, M. Craghan, J. Haines, J.F. Hart, H. Stiller, and A. Sutton-Grier, 2018: Coastal Effects. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 313–343. doi: 10.7930/NCA4.2018.CH8

On the Web: https://nca2018.globalchange.gov/chapter/coastal-effects

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.

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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

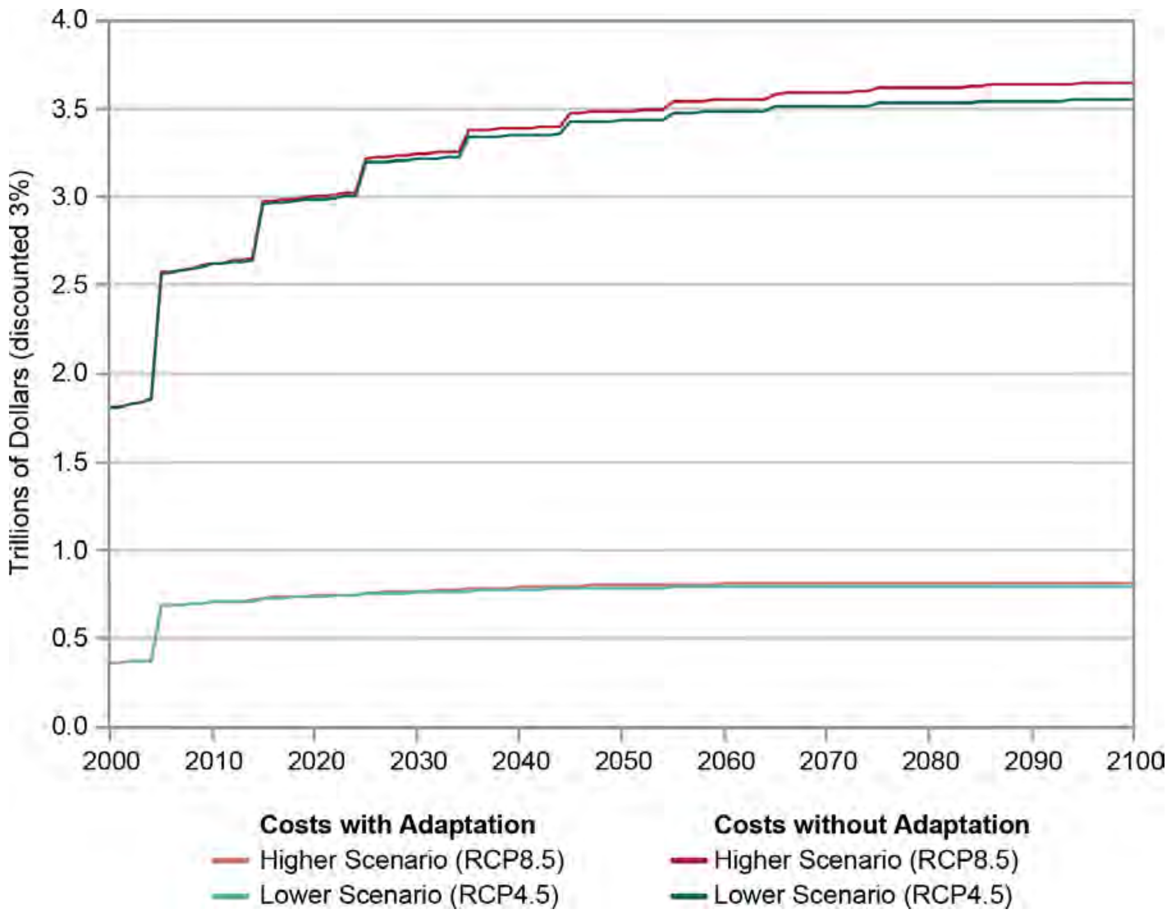


Figure 8.1: This figure shows that cumulative damages (in 2015 dollars) to coastal property across the contiguous United States would be significantly reduced if protective adaptation measures were implemented, compared to a scenario where no adaptation occurs. Without adaptation, cumulative damages 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

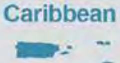
	Impact	Adaptation Efforts
Northeast 	Recurrent coastal flooding	The cities of Binghamton, New York, and Boston, Massachusetts, promote the use of green infrastructure to build resilience, particularly in response to flooding risk.
Southeast 	Sea level rise	Charleston, South Carolina, has developed a 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

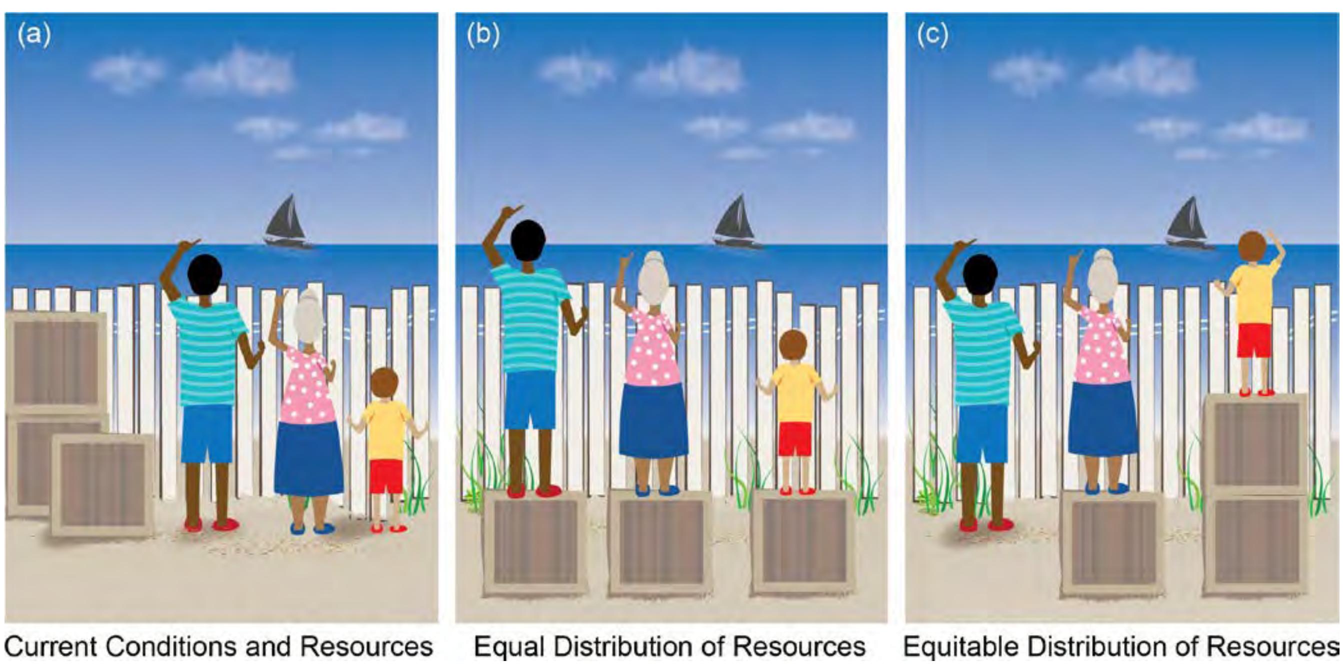


Figure 8.5: Society has limited resources to help individuals and communities adapt to climate change. Panel (a) illustrates that there are finite resources available and that individuals and communities are starting from different levels of readiness to adapt. Panel (b) illustrates the option for society 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

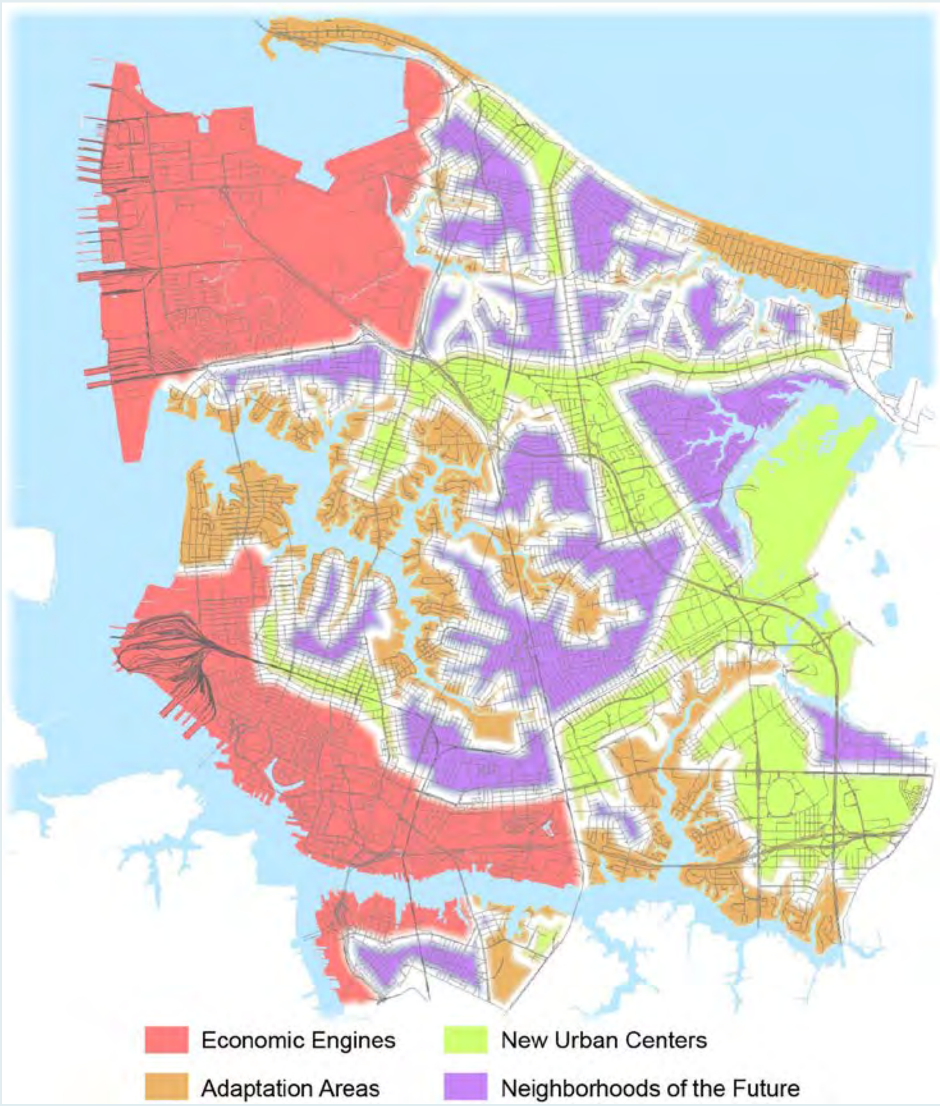


Figure 8.7: The City of Norfolk is building a long-term strategy to address the flooding challenges due to sea level rise. Green areas are at low risk of coastal flooding and have great potential for high-density, mixed-use, and mixed-income development. Red areas are home to key economic assets that 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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Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

Oceans and Marine Resources

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Recommended Citation for Chapter

Pershing, A.J., R.B. Griffis, E.B. Jewett, C.T. Armstrong, J.F. Bruno, D.S. Busch, A.C. Haynie, S.A. Siedlecki, and D. Tommasi, 2018: Oceans and Marine Resources. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 344–381. doi: 10.7930/NCA4.2018.CH9

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

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

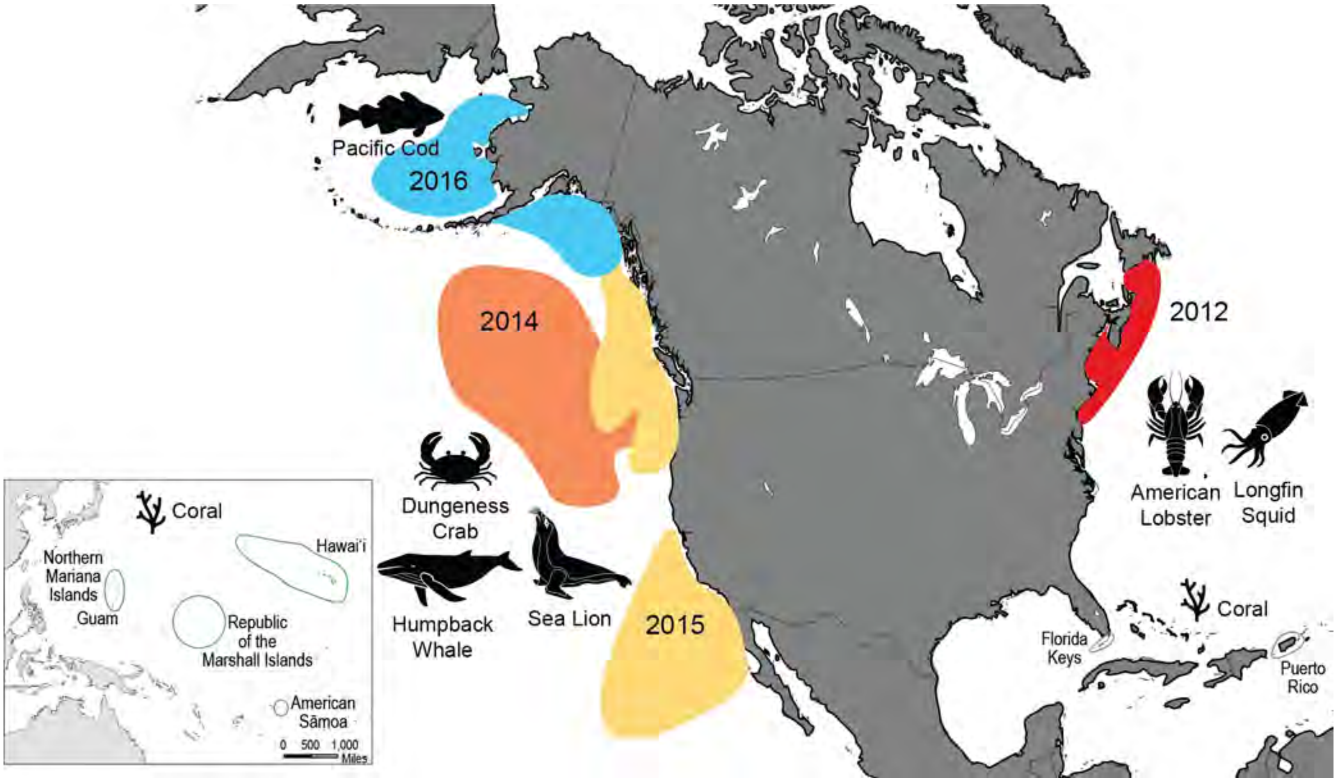
Americans rely on ocean ecosystems for food, jobs, recreation, energy, and other vital services. Increased atmospheric carbon dioxide levels change ocean conditions through three main factors: warming seas, ocean acidification, and deoxygenation. These factors are transforming ocean ecosystems, and these 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, Hawaiʻi, and the U.S.-Affiliated Pacific Islands (Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawaiʻi & 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]

Marine Ecosystem Services

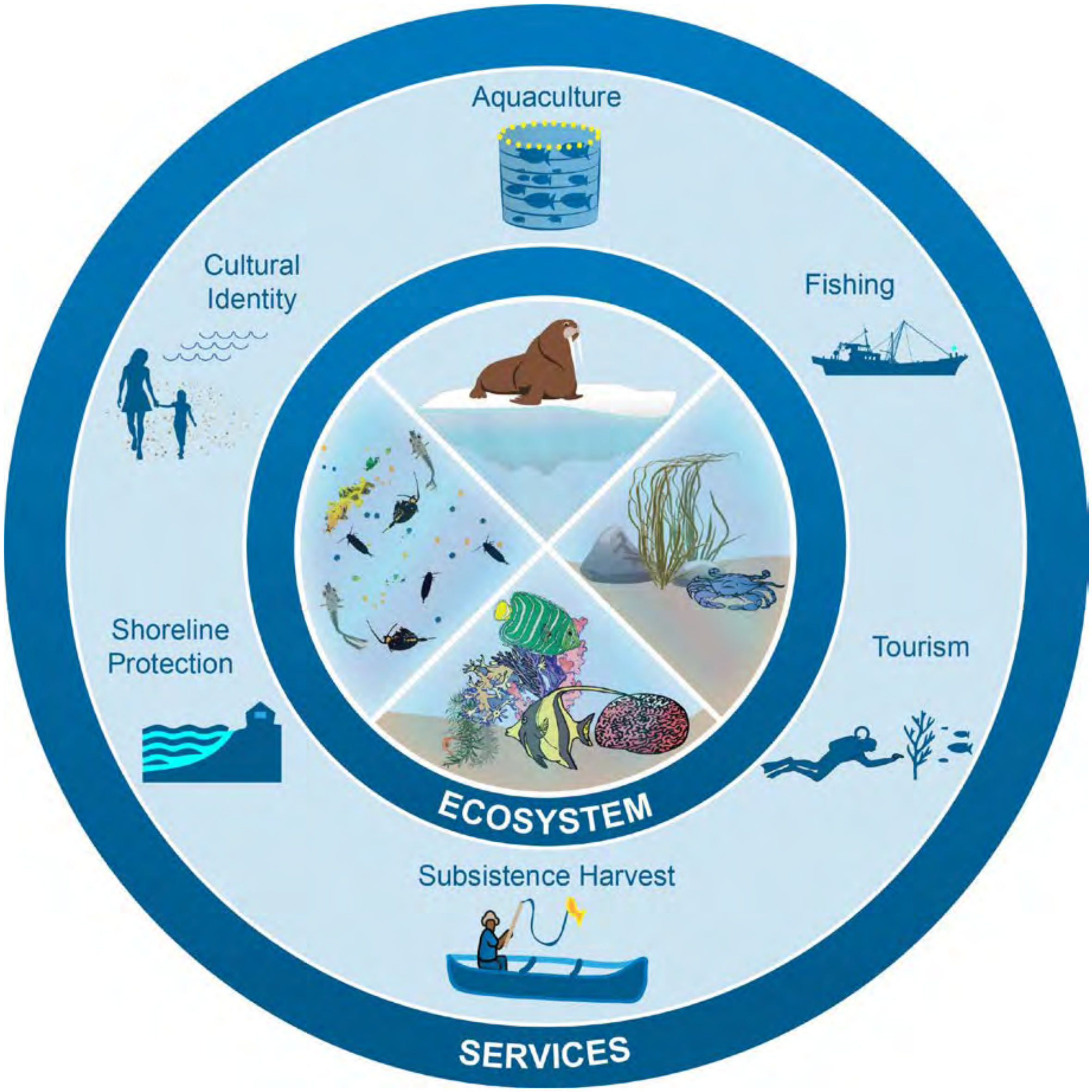


Figure 9.1: The diagram shows some marine ecosystems (center) and the services they provide to human communities (outer ring). Marine ecosystems in the United States range from tropical coral reefs (center bottom) to sea ice ecosystems in the Arctic (center top). They also include ecosystems with freely 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

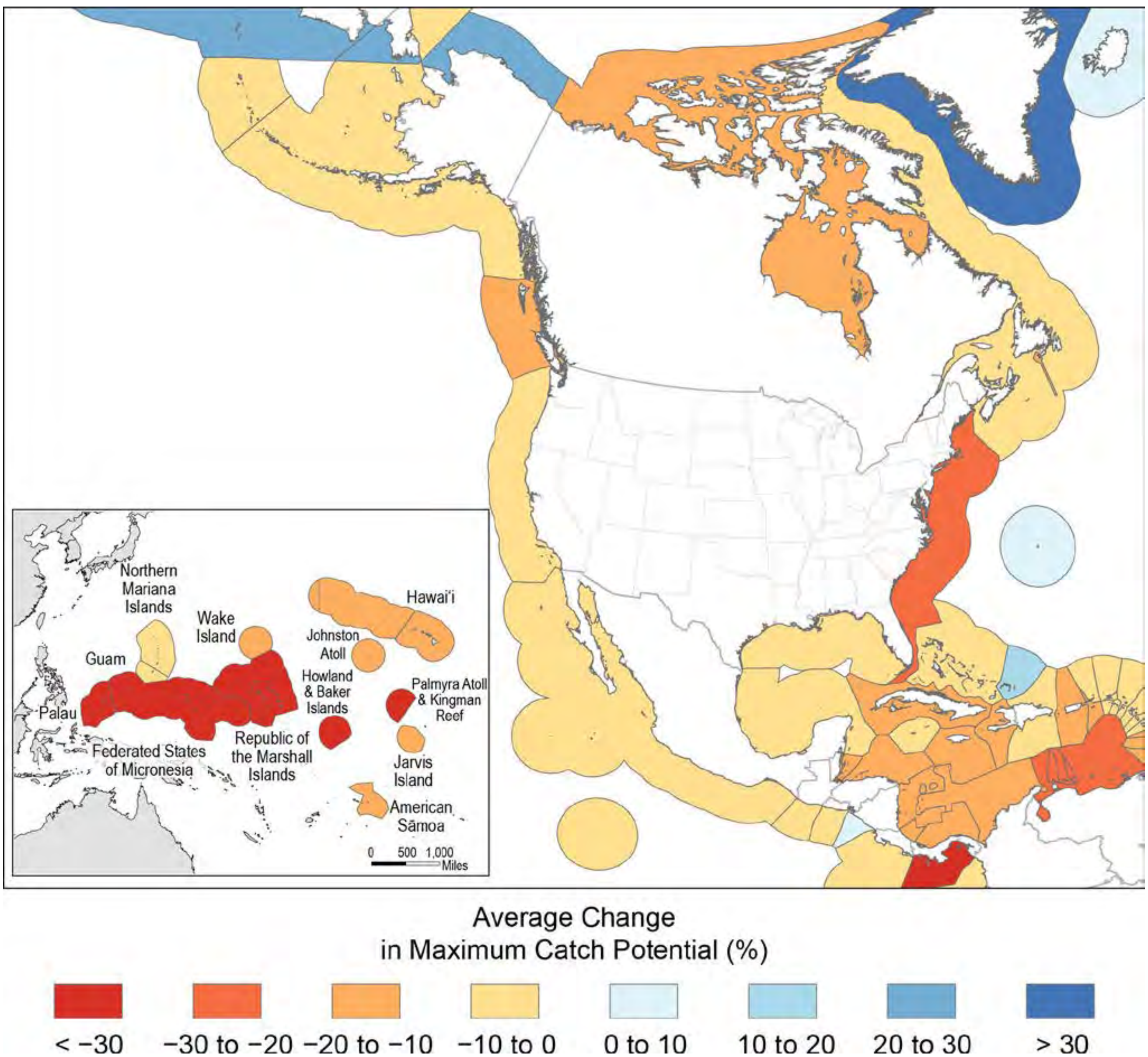


Figure 9.2: The figure shows average projected changes in fishery catches within large marine ecosystems for 2041–2060 relative to 1991–2010 under a higher scenario (RCP8.5). All U.S. large marine ecosystems, with the exception of the Alaska Arctic, are expected to see declining fishery catches. Source: 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.

Extreme Events in U.S. Waters Since 2012

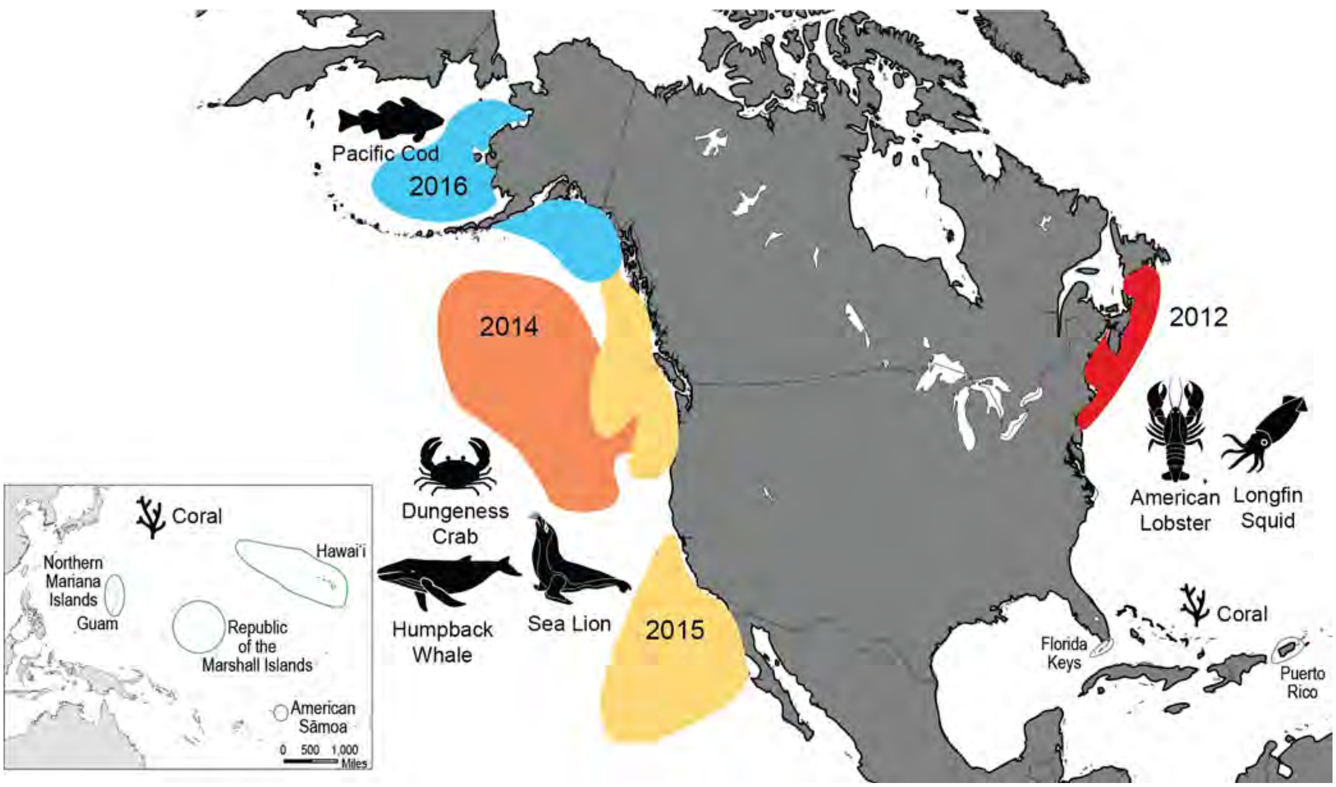


Figure 9.3: The 2012 North Atlantic heat wave was concentrated in the Gulf of Maine; however, shorter periods with very warm temperatures extended from Cape Hatteras to Iceland during the summer of 2012. American lobster and longfin squid and their associated fisheries were impacted by the event.[1] 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.

Acknowledgments

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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: Hawaiʻi & 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 con- ditions 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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