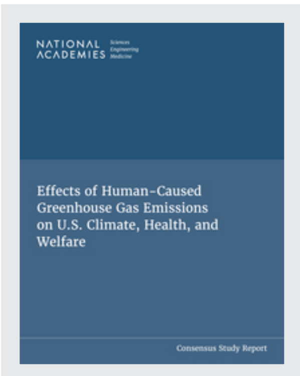

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CONTRIBUTORS

Committee on Anthropogenic Greenhouse Gases and U.S. Climate: Evidence and Impacts; Climate Crossroads; Board on Atmospheric Sciences and Climate; Board on Health Sciences Policy; National Research Council Executive Office; Division on Earth and Life Studies; Health and Medicine Division; National Academies of Sciences, Engineering, and Medicine

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Effects of Human-Caused Greenhouse Gas Emissions on U.S. Climate, Health, and Welfare

Committee on Anthropogenic Greenhouse Gases and U.S. Climate: Evidence and Impacts

Climate Crossroads

Board on Atmospheric Sciences and Climate

Board on Health Sciences Policy

National Research Council Executive Office

Division on Earth and Life Studies

Health and Medicine Division

Consensus Study Report

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COMMITTEE ON ANTHROPOGENIC GREENHOUSE GASES AND U.S. CLIMATE: EVIDENCE AND IMPACTS

SHIRLEY M. TILGHMAN (NAS/NAM) (*Chair*), Princeton University
DAVID T. ALLEN (NAE), The University of Texas at Austin
SUSAN ANENBERG, The George Washington University
MICHELE BARRY (NAM), Stanford University
CHARLES T. DRISCOLL, JR. (NAE), Syracuse University
SUSAN HANSON (NAS), Clark University (retired)
CHRIS T. HENDRICKSON (NAE), Carnegie Mellon University
MARIKA HOLLAND, National Science Foundation National Center for Atmospheric Research
GEORGE M. HORNBERGER (NAE), Vanderbilt University
ARTHUR LEE, Chevron (retired)
KARI C. NADEAU (NAM), Harvard University
CHARLES W. RICE, Kansas State University
DREW T. SHINDELL (NAS), Duke University
GRAEME L. STEPHENS (NAE), NASA Jet Propulsion Laboratory
DAVID W. TITLEY, Rear Admiral, U.S. Navy (retired)
JOHN C. WALL (NAE), Cummins, Inc. (retired)

Study Staff

AMANDA STAUDT, Senior Director of Climate Crossroads
KASEY WHITE, Director of the Board on Atmospheric Sciences and Climate
APRIL MELVIN, Associate Director of the Polar Research Board and Senior Program Officer with the Board on Atmospheric Sciences and Climate
KATHERINE BOWMAN, Senior Program Officer with the Board on Health Sciences Policy
AMANDA PURCELL, Associate Director and Senior Program Officer with Climate Crossroads
LINDSAY MOLLER, Research Associate with the Board on Atmospheric Sciences and Climate
NANCY HUDDLESTON, Communications Director with the Division on Earth and Life Studies
MADDI NICOL, Senior Program Assistant with the Division on Engineering and Physical Sciences

NOTE: See Appendix B, Disclosure of Unavoidable Conflicts of Interest.

Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

MAUREEN CROPPER (NAS), University of Maryland, College Park
KRISTIE EBI, University of Washington
RONG FU (NAE), University of California, Los Angeles
INEZ FUNG (NAS), University of California, Berkeley
TIMOTHY GALLAUDET, U.S. Navy (retired)
LYNN GOLDMAN (NAM), The George Washington University
SARAH HOBBIE (NAS), University of Minnesota
DIANA LIVERMAN (NAS), University of Arizona
HUSSAM MAHMOUD, Vanderbilt University
KATHERINE McCOMAS, Cornell University
RICHARD MESERVE (NAE), Carnegie Institution for Science
WILLIAM PRESS (NAS), The University of Texas at Austin
ERIC RIGNOT (NAS/NAE), University of California, Irvine
ROBERT ROHDE, Berkeley Earth
CATHIE WOTEKI (NAM), Iowa State University

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by **KAI N. LEE,** Center for Ocean Solutions, Stanford University, and Owl of Minerva, LLC, and **CYNTHIA M. BEALL (NAS),** Case Western Reserve University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Contents

Foreword

The U.S. Environmental Protection Agency (EPA) concluded that "six greenhouse gases taken in combination endanger both the public health and the public welfare of current and future generations" in its 2009 "Endangerment Finding." In a Federal Register Notice published on August 1, 2025, EPA stated that the agency "unreasonably analyzed the scientific record" in making the 2009 Endangerment Finding and that subsequent "developments cast significant doubt on the reliability of the findings." Such significant claims about the scientific record deserve careful review. The Federal Register Notice proposed repealing the Endangerment Finding and invited public comments.

In response to EPA's request for public input, the National Academies of Sciences, Engineering, and Medicine undertook this independent assessment of the science underpinning the Endangerment Finding. In the Clean Air Act, the U.S. Congress instructed EPA to draw on findings, recommendations, and comments from the Clean Air Science Advisory Committee (CASAC) and the National Academy of Sciences (NAS) (42 U.S. Code § 7607(D)(3)(c)). Advice from CASAC was not available to EPA during the window when it was considering this proposed rulemaking because CASAC was disbanded in January 2025, and EPA was in the process of appointing new members (Federal Register Doc. 2025-07538 (90 FR 18658)).

Supporting evidence-informed decision-making by the federal government is a core mission of the National Academies. This study was produced to meet the timeline of the Federal Register Notice (August 1–September 22, 2025) and followed the standard National Academies' processes for managing conflicts of interest, inviting public comment on the committee members, and thorough peer review of the draft report.

This study was supported by the NAS, using funding from two of its endowments. The Arthur L. Day Fund was created for studies on physics of the Earth; its namesake was an expert in geophysics and volcanology who served as vice president of NAS from 1933 to 1941. The Ralph J. Cicerone and Carol M. Cicerone Fund was created to honor the service of Dr. Ralph Cicerone, president of NAS from 2005 to 2016.

I am deeply grateful to Dr. Shirley Tilghman, who ably chaired this committee, and to all of the members and staff who worked tirelessly to complete this report in a timely manner.

Marcia McNutt
President
National Academy of Sciences

Preface

As the committee undertook this project, it was hard not to think about recent climate-related disasters: the heavy rainfall of Hurricane Helene that destroyed homes and roads in the mountains of North Carolina, the fast-moving wildfires that displaced thousands in Los Angeles and affected air quality for miles around, and the rapid flooding of the Guadalupe River in central Texas that led to at least 135 fatalities. The U.S. Environmental Protection Agency (EPA) concluded in 2009, based on scientific understanding at the time, that emitting greenhouse gases (GHGs) to the atmosphere increased the risk of harms to human health and welfare from changes to the climate, including the risks associated with hurricanes, wildfires, and heavy rainfall, among many others. On the strength of this "Endangerment Finding," EPA and many state governments instituted their own regulations governing GHG emissions in the intervening years.

In August 2025, EPA issued a notice of proposed rulemaking to rescind the Endangerment Finding. This 2009 finding by the EPA Administrator was informed by a companion Technical Support Document (EPA, 2009a) that laid out the scientific evidence that emissions of six GHGs posed a threat to human health and welfare. With the aim of informing EPA as it considers the status of the Endangerment Finding, the National Academies undertook this study to evaluate the current state of scientific evidence regarding the impact of human-caused GHGs on climate, with a particular focus on the evidence in the peer-reviewed primary literature that has accumulated since 2009.

Specifically, the committee asked whether new evidence since 2009 strengthened or weakened the primary conclusions in the original EPA report (2009a) and addressed uncertainties that remain in our understanding of the science of climate change. In addition, the committee identified new issues that were not evident or addressed in the EPA report (2009a). Although climate change in response to GHG emissions is a global issue, the committee concentrated on the effects on human health and welfare in the United States in order to address the statutory concern of EPA. The committee's charge was to produce a succinct and balanced evaluation of the state of the science, not to make recommendations or advocate for a specific policy. We hope that the report will serve as a critical resource in informing U.S. federal agency decision-making regarding future GHG regulations.

The importance of getting the science right weighed heavily on the committee's deliberations, given the potential significant implications of a changing climate and of the actions proposed to address it. Unlike earthquakes and volcanoes, over which we have no control, responding to the potential harm to human health and welfare from changes in the climate is actionable now. While the short timeline of the study did not lend itself to holding open discussion sessions in person, the committee is grateful to the more than 200 individuals and organizations who responded to a Request for Information. These inputs helped the committee survey the breadth of the literature that has been published since 2009, pointing it to more than 600 peer-reviewed articles. Many of those contributions have been incorporated into the report and influenced its conclusions.

I am deeply grateful to the 15 distinguished scientists, engineers, and physicians on the committee who so generously gave their time and expertise to produce the report. They would not have succeeded without the logistical, managerial, and editorial support of the National Academies' staff, ably led by Amanda Staudt—Katherine Bowman, Nancy Huddleston, April Melvin, Lindsay Moller, Maddi Nicol, Amanda Purcell, and Kasey White. Everyone, including those who participated in the report review process, was inspired by the importance of the task at hand and contributed significantly to the final report.

Shirley M. Tilghman, *Chair*
Committee on Anthropogenic Greenhouse Gases and U.S. Climate: Evidence and Impacts
September 2025

Summary[1]

The scientific community has been studying the question of how human-caused emissions of greenhouse gases are affecting the climate for well over a century. Much is known today, drawing upon decades of direct observations of the Earth system and detailed research. In this report, the committee summarizes the latest evidence on whether greenhouse gas (GHG) emissions threaten human health and welfare in the United States.

The impetus for this report was a notice of proposed rulemaking issued by the U.S. Environmental Protection Agency (EPA) indicating its intention to rescind the 2009 action titled "Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act." Recognizing that significantly more evidence is available today, the National Academies of Sciences, Engineering, and Medicine launched this study to review newly available scientific evidence on the topics considered in the Technical Support Document that EPA prepared in considering whether to make the finding (see Box 1.2 for the Statement of Task). The committee's report focuses on evidence gathered by the scientific community since the Technical Support Document was published in 2009 and describes supporting evidence, the level of confidence, and areas that are under continuing debate or are unknown.

On the basis of the scientific evidence outlined in the body of this report, the committee reached the following overarching conclusion:

Overarching Conclusion: EPA's 2009 finding that the human-caused emissions of greenhouse gases threaten human health and welfare was accurate, has stood the test of time, and is now reinforced by even stronger evidence. Today, many of EPA's conclusions are further supported by longer observational records and multiple new lines of evidence. Moreover, research has uncovered additional risks that were not apparent in 2009.

This overarching conclusion is supported by the following five conclusions:

(1) **Emissions of greenhouse gases from human activities are increasing the concentration of these gases in the atmosphere.** Human activities—such as the extraction and burning of fossil fuels, cement and chemical production, deforestation, and agricultural activities—emit GHGs, which include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases), to the atmosphere. Total global GHG

[1] This summary does not include references. Citations for the information presented herein are provided in the main text.

emissions continue to increase, even though U.S. emissions of CO_2 have decreased slightly in recent years largely due to changes in energy production and consumption. Multiple lines of evidence show that GHG emissions from human activities are the primary driver of the observed long-term warming trend. No known natural drivers, such as incoming solar radiation or volcanic emissions, can explain observed changes.

(2) **Improved observations confirm unequivocally that greenhouse gas emissions are warming Earth's surface and changing Earth's climate.** Longer records, improved and more robust observational networks, and analytical and methodological advances have strengthened detection of observed changes and their attribution to elevated GHGs. Trends observed include increases in hot extremes and extreme single-day precipitation events, declines in cold extremes, regional shifts in annual precipitation, warming of the Earth's oceans, a decrease in ocean pH, rising sea levels, and an increase in wildfire severity.

(3) **Human-caused emissions of greenhouse gases and resulting climate change harm the health of people in the United States.** Climate change intensifies risks to humans from exposures to extreme heat, ground-level ozone, airborne particulate matter, extreme weather events, and airborne allergens, affecting incidence of cardiovascular, respiratory, and other diseases. Climate change has increased exposure to pollutants from wildfire smoke and dust, which has been linked to adverse health effects. The increasing severity of some extreme events has contributed to injury, illness, and death in affected communities. Health impacts related to climate-sensitive infectious diseases—such as those carried by insects and in contaminated water—have increased. New evidence is developing about additional health impacts of climate change, including on mental health, nutrition, immune health, antimicrobial resistance, kidney disease, and negative pregnancy-related outcomes. Groups such as older adults, people with preexisting health conditions or multiple chronic diseases, and outdoor workers are disproportionately susceptible to climate-associated health effects. Even as non-climate factors, including adaptation measures, can help people cope with harmful impacts of climate change, they cannot remove the risk of harm.

(4) **Changes in climate resulting from human-caused emissions of greenhouse gases harm the welfare of people in the United States.** Climate-driven changes in temperature and precipitation extremes and variability are leading to negative impacts on agricultural crops and livestock, even as technological and other changes have increased agricultural production. Climate change, including increases in climate variability and wildfires, is changing the community composition and function of forest and grassland ecosystems and the services they provide. Climate-related changes in water availability and quality vary across regions in the United States with some regions showing a decline. Climate-related changes in the chemistry and the heat content of the ocean are having negative effects on calcifying organisms and contributing to increases in harmful algal blooms. U.S. energy systems, infrastructure, and many communities are experiencing increasing stress and costs owing to the effects of climate change.

(5) **Continued emissions of greenhouse gases from human activities will lead to more climate changes in the United States, with the severity of expected change increasing with every ton of greenhouse gases emitted.** Despite successful efforts in many parts of the world to reduce emissions, total global GHG emissions have continued to increase, and additional warming is certain. All climate models—regardless of assumptions about future emissions scenarios or estimates of climate sensitivity—consistently project continued warming in response to future atmospheric GHG increases. Applying fundamental physics of the Earth system leads to the same conclusion. Continued changes in the climate increase the likelihood of passing thresholds in Earth systems that could trigger tipping points or other high-impact climate surprises.

In summary, the committee concludes that the evidence for current and future harm to human health and welfare created by human-caused GHGs is beyond scientific dispute. Much of the understanding of climate change that was uncertain or tentative in 2009 is now resolved, and new threats have been identified. These new threats and the areas of remaining uncertainty are under intensive investigation by the scientific community. The United States faces a future in which climate-induced harm continues to worsen and today's extremes become tomorrow's norms.

1

Introduction

In 1896, Svante Arrhenius made a bold hypothesis: If gases that absorb heat energy are added to Earth's atmosphere, then science could quantify how much the average temperature of the Earth would increase (Arrhenius, 1896). This hypothesis was based on earlier laboratory experiments showing that carbon dioxide (CO_2) and water molecules absorb energy, specifically at wavelengths typically emitted as heat from the Earth's surface (Foote, 1856; Tyndall, 1863). Gathering evidence to test the quantification of planetary-scale effects of changing the composition of the atmosphere would be much more challenging.

Climate records from weather stations and ship logs extend back to the 1700s, but it was not until the late 1950s, during the International Geophysical Year, that multiple scientific disciplines came together to more fully observe the Earth system (McCahey, 2025). The first continuous monitoring of atmospheric CO_2 began at this time (Keeling et al., 2001). Since then, an expanding array of increasingly sophisticated evidence, spanning many aspects of the climate system and the natural environment, has enabled the scientific community to test Arrhenius' hypothesis.

An upward trend in atmospheric CO_2 was documented by the early 1960s, confirming expectations that human activities during the industrial era were changing the concentration of CO_2 in the atmosphere (Keeling et al., 2001). Nonetheless, recognizing the large variability inherent to the climate system, scientists made sure that the long-term trend was robust before drawing conclusions about the potential global impact of increases in CO_2. For example, the National Research Council first addressed the topic in a 1979 report, 20 years after atmospheric CO_2 measurements were available (NRC, 1979).

These early climate change studies discussed the many uncertainties and unknowns that have been the subject of research over the intervening years. At the same time, these reports called attention to the potentially critical implications for people and the environment of changing climate and stressed the importance of science to inform policy decisions. The foreword to the 1979 NRC report stated that its conclusions might be "disturbing to policymakers," noting that "a wait-and-see policy may mean waiting until it is too late."

This report provides an updated overview of the scientific evidence related to emissions of long-lived greenhouse gases (GHGs) to the atmosphere, how the changing atmospheric composition is affecting the climate system, and the impacts on human health and welfare. It is intended to inform policymakers, and the public more generally, as they navigate many climate-sensitive decisions.

1.1 STUDY CHARGE

On August 1, 2025, the U.S. Environmental Protection Agency (EPA) issued a notice titled "Reconsideration of 2009 Endangerment Finding and Greenhouse Gas Vehicle Standards," which proposed rulemaking to rescind its prior findings that GHG emissions endanger human health and welfare (see Box 1.1) and invited public comments on its proposal (EPA, 2025i). The "Endangerment Finding" was made by the EPA Administrator in 2009 (EPA, 2009b) and was informed by a Technical Support Document that reviewed scientific evidence available at the time (EPA, 2009a). Recognizing that significantly more is known today, the National Academies launched this study to review newly available scientific evidence. To best inform EPA's decision process, the study was completed during the public comment period.

The current study committee was charged to review the latest scientific evidence on whether GHG emissions are reasonably anticipated to endanger public health and welfare in the United States (see Box 1.2). The report focuses on evidence gathered by the scientific community since the publication of the Endangerment Report's Technical Support Document (EPA, 2009a) and describes supporting evidence, the level of confidence, and areas of disagreement or unknowns.

This report does not address other factors that EPA considers in determining whether to regulate emissions. The question raised in the proposed rulemaking of whether EPA has authority to regulate GHGs to address climate change under section 202(a) of the Clean Air Act is outside the scope of the report. The committee addresses the question of whether future emissions could cause or contribute to future harm but does not consider specific scenarios in detail. Quantifying how emissions from new motor vehicles or engines (as well as other non-vehicle sources) might cause or contribute to future GHG emissions requires information about future technology developments and regulatory scope, which is unavailable to the committee. Addressing the feasibility of reducing emissions from motor vehicles and other sources is outside the scope of this report but has been considered by other National Academies studies (e.g., NASEM, 2021a, 2024a). Finally, the committee did not take up the question of whether proposed regulations impose an undue economic burden. Such an assessment would require more detailed information about proposed regulations and considerable further analysis of economic implications.

BOX 1.1
The "Endangerment Finding"

The U.S. Supreme Court's 2007 decision in *Massachusetts v. Environmental Protection Agency* (549 U.S. 497, 2007) held that carbon dioxide (CO_2) and other greenhouse gases (GHGs) fall within the statutory definition of an "air pollutant" in the Clean Air Act (CAA). As a result, EPA was required to determine whether GHGs endanger public health or welfare, whether emissions from mobile sources cause or contribute to that endangerment, and if so, whether those emissions should be subject to regulation.

In 2009, EPA released "Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act," (74 FR 66496, referred to as the Endangerment Finding). In this finding, the EPA Administrator concluded that "six greenhouse gases taken in combination endanger both the public health and the public welfare of current and future generations" and that "the combined emissions of these greenhouse gases from new motor vehicles and new motor vehicle engines contribute to the greenhouse gas air pollution that endangers public health and welfare under CAA section 202(a)." These conclusions were based on a review of available scientific literature, summarized in a companion Technical Support Document (EPA, 2009a). The conclusions highlighted in the Executive Summary of EPA (2009a) are included in Appendix C of this report.

BOX 1.2
Statement of Task

This fast-track study will review evidence for whether anthropogenic emissions of greenhouse gases to the atmosphere are reasonably anticipated to endanger public health and welfare in the United States. The study will focus on updates since the Environmental Protection Agency finalized the Endangerment Finding in 2009, examine how current understanding compares to the 2009 Endangerment Finding, and provide explanation for any changes. The study will develop conclusions that describe supporting evidence, the level of confidence, and areas of disagreement or unknowns.

1.2 REPORT STRUCTURE

The causal chain from GHG emissions through impacts on human health and public welfare is shown in Figure 1.1. Assessing the impact of human-caused GHG emissions requires examining the evidence for each step in this causal chain, as well as understanding the mechanisms that link the steps. The report is organized to examine the evidence as follows:

- Chapter 2 examines observed changes in natural and human-caused GHG emissions, how those emissions are changing the atmospheric concentration of GHGs, and the impact of those changes on the energy imbalance at the surface of the Earth;
- Chapter 3 examines observed changes in climate conditions at the global and regional scales and the attribution of those climate changes to changes in human-caused GHG emissions;
- Chapter 4 addresses potential impacts of changes in GHGs on future climate, informed by the evidence discussed in Chapters 2 and 3;
- Chapter 5 addresses the impacts of changes in GHGs and changing climate conditions on human health; and
- Chapter 6 addresses the impacts of changing climate conditions on public welfare.

While this report focuses on the pathway by which changes in GHGs affect human health and public welfare, many other non-climate factors also influence the impacts, as illustrated in Figure 1.1. Non-climate factors can include changes in technologies or practices, changes in human systems (e.g., infrastructure, land use), changes in other environmental stressors (e.g., pollution), and other factors that exacerbate or mitigate the impacts of human-caused GHG emissions. The committee discusses non-climate factors, where significant, in examining impacts of changes in climate in Chapters 5 and 6.

1.3 COMMITTEE'S APPROACH

This report summarizes the changes in evidence since 2009 for each step in the causal chain shown in Figure 1.1, recognizing that the nature of the evidence and uncertainty varies across the different links in this causal chain and for different impacts. The committee considered the science detailed in EPA's Technical Support Document (2009a) as the state of the science that informed EPA's 2009 Endangerment Finding (2009b). Recognizing that EPA (2009a) covered a wide array of topics, the committee focused on those topics highlighted in the Executive Summary of the document (see Appendix C). In addition, the committee identified other topics, including those covered in the body of EPA (2009a) but not highlighted in its Executive Summary, for which new lines of discovery or impacts have emerged. The selection of topics to highlight was informed, in part, by reviewing submissions to a public Request for Information (RFI).

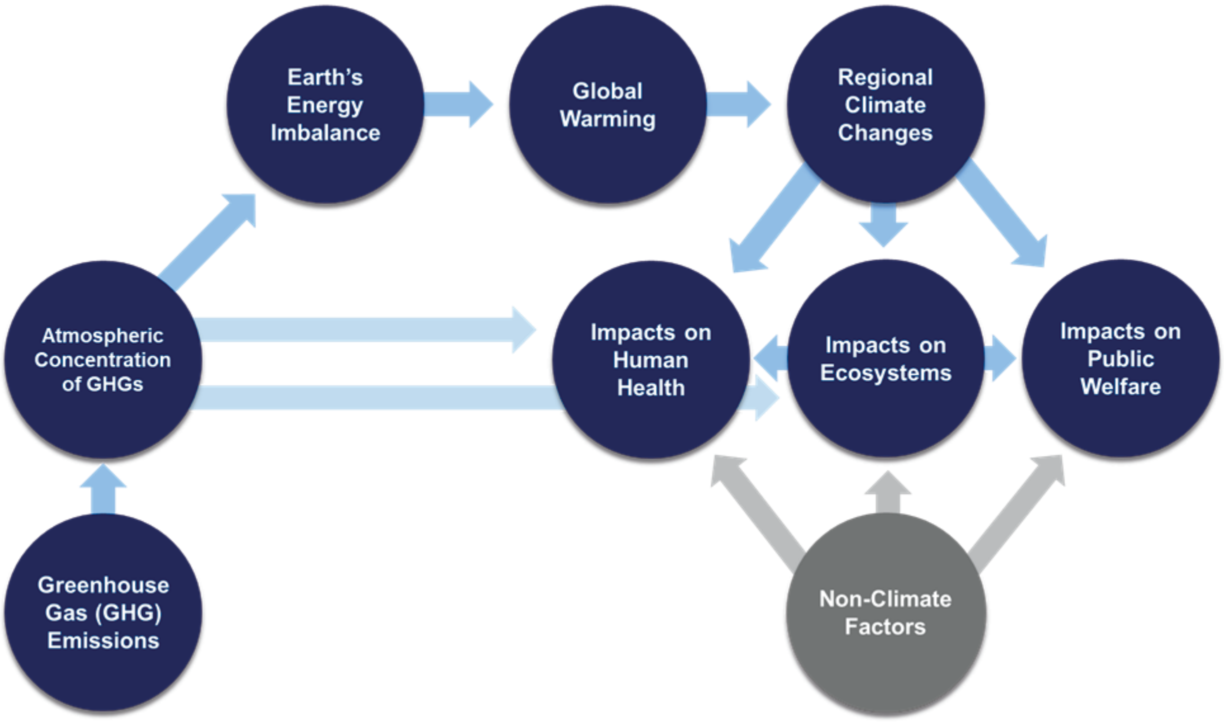


FIGURE 1.1 Schematic of the causal chain from GHG emissions to impacts on human health and public welfare, indicated by the darker blue arrows. The potential direct impacts of GHG emissions on human health (e.g., through contribution to air pollution) and on ecosystems (e.g., changes in ocean chemistry) are indicated by the lighter blue arrows. Non-climate factors, indicated by the grey circle and arrows, include changes in technologies or practices, changes in human systems (e.g., infrastructure, land use), changes in other environmental stressors (e.g., pollution), and other factors that exacerbate or mitigate the impacts of human-caused GHG emissions.

In developing the conclusions of this report, the committee relied upon multiple sources of evidence and considered conclusions to be stronger if there is broad agreement among independent lines of evidence. The specific type of evidence relevant and available for each conclusion varies. The committee weighed most heavily observational evidence, which includes direct measurements of physical, chemical, or biological quantities; observations from space-based platforms and other instruments that remotely sense the atmosphere, ocean, and biosphere; surveys of ecological variables; and inventories and records of human systems (e.g., emissions data from industrial sources or epidemiological studies). The committee also evaluated evidence from computational climate models that simulate the Earth system. These models are an important line of evidence considered in this report. That said, the climate system is complex, and climate models are imperfect tools; therefore, the committee relied more heavily on observational evidence.

To prepare this report, the committee considered (1) widely available datasets that provide information about GHG emissions, changes to the climate system, and human health and public welfare impacts; (2) a broad range of peer-reviewed literature and scientific assessments; and (3) more than 200 comments submitted in response to a public RFI and through the standard feedback channels for National Academies' activities. In keeping with the study charge, the committee focused on literature published since 2009 and on impacts to public health and welfare in the United States.

The committee examined scientific papers in the peer-reviewed literature, focusing on areas where there have been significant new contributions that have changed or expanded understanding. Where available, the committee drew on scientific assessments and reports by the National Academies that have been prepared by large teams of scientists, incorporate mechanisms for broad public input, and are subject to additional layers of peer review. These large-scale efforts provide periodic updates on the state of knowledge. The committee tried to strike a balance between directly citing original studies and drawing upon assessments, recognizing that both types of analyses provide useful information. Published assessments, reports, and scientific papers provided useful input; however, it is important to note that the committee then made its own determinations about how the evidence and understanding have changed since 2009 in the key messages and conclusions of this report.

The EPA notice of proposed rulemaking cited a document, “A Critical Review of Impacts of Greenhouse Gas Emissions on the U.S. Climate,” authored by a Climate Working Group assembled by the Secretary of Energy.[1] This document was made available in draft form on July 29, 2025, at which point the U.S. Department of Energy invited public comment and indicated that it would be revised. Because this document was not available in its final form and may change in response to comments received, the committee does not cite it. Nonetheless, there is significant overlap in the topics addressed and in some of the literature cited in the document and this committee’s report. For example, the committee addresses the direct impacts of CO_2 on the environment in a discussion of ocean heat and chemistry in Chapter 3 and in a discussion of the drivers of ecosystem change in Chapter 6.

1.4 GEOGRAPHIC FOCUS OF THE REPORT

The climate varies significantly across the United States, ranging from tropical to Arctic temperatures and a wide range of precipitation regimes. Observed changes in the climate system similarly exhibit regional variability. The factors that influence human health and welfare also vary across regions, reflecting the differing geographies, ecosystems, infrastructures, economic activities, and recreation activities found across the country. This report highlights selected regional differences in climate effects and provides examples of regionally specific impacts, but it does not include a comprehensive assessment of climate impacts in specific regions.

The committee focused on impacts to human health and welfare in the United States, similar to the scope of EPA (2009a). The Clean Air Act requires the EPA Administrator to take actions to safeguard the American people. Thus, this report focuses on the risks to the U.S. population, who are most directly affected by changes in climate conditions within its borders. In addition, the committee considered changes to global oceans and the effects of these changes on U.S. coasts and fisheries.

EPA (2009a) includes a section on impacts in other world regions, but the committee did not address these impacts in detail. Even so, it is worth noting that changes to climate conditions in other parts of the world do affect Americans. Many U.S. businesses are multinational, some with climate-sensitive operations (e.g., supply chain agreements, shipping, agriculture). Many Americans live in other parts of the world—in U.S. territories, as members of the armed forces and Foreign Service, and as part of a large American expatriate population—and these places face their own climate risks. A growing body of research has examined how climate stresses in other parts of the world can indirectly affect U.S. national security (e.g., increasing migration pressures or creating political instability) (DOD, 2021; NASEM, 2023).

1.5 HUMAN HEALTH AND PUBLIC WELFARE IMPACTS CONSIDERED

Climate affects human health and welfare in a multitude of ways, influencing everything from how land is used for agriculture to how and where buildings are constructed to the diseases and other health risks prevalent in different locations. As a result, the potential scope for the effects of GHGs on welfare is particularly vast. The Clean Air Act identifies many effects that fall under “welfare” and leaves open applications to other areas, as well. Section 302(h) of the Act (42 U.S.C. § 7602[h]) states: “All language referring to effects on welfare includes, but is not limited to, effects on soils, water, crops, vegetation, man-made materials, animals, wildlife, weather, visibility, and climate, damage to and deterioration of property, and hazards to transportation, as well as effects on economic values and on personal comfort and well-being.”

[1] See https://www.federalregister.gov/documents/2025/08/01/2025-14519/notice-of-availability-a-critical-review-of-impacts-of-greenhouse-gas-emissions-on-the-us-climate.

Given the very broad definition of welfare in the Clean Air Act and the broad scope covered in EPA (2009a), an exhaustive review of the rapidly growing body of literature on potential effects was not feasible in this short report. In the discussion of impacts in Chapters 5 and 6, the committee chose to focus on potential impacts with (1) more direct attribution to changes in climate conditions, and (2) more direct impacts on human health and well-being. This choice is not intended to minimize the numerous more complex or indirect ways that changing climate conditions affect people and nature. Rather it reflects the committee's determination that the evidence presented for this subset of impacts is sufficient to support their conclusions regarding endangerment.

This report highlights examples of economic analyses but does not attempt an exhaustive review of the growing body of literature related to economic impacts of GHGs or climate changes. Furthermore, studies on future economic impacts are not included. Predicting potential future economic impacts requires assumptions about many factors unrelated to climate that affect society and markets.

Similar to EPA (2009a), this report does not consider the potential of adaptation measures to limit future impacts on public health and welfare. In making a finding of endangerment, the Clean Air Act requires only scientific determination of risk of harm, without speculation of potential actions that might be taken to limit that harm. Predicting the efficacy of potential future adaptation actions to limit that risk requires assumptions about human behavior, government policies, technological advances, and many other factors unrelated to climate.

Finally, the last century has been a time of rapid population growth, urbanization, increases in per capita consumption, and technological innovation. This report describes a range of factors, as illustrated in Figure 1.1, that significantly affect human health and welfare, recognizing that the impacts of changing climate occur in combination with other changing conditions. For example, trends in economic damages from extreme weather events depend on changes in the frequency, severity, or location of extreme weather in combination with changes in where people live and the value of property located in vulnerable places. This report draws on the large body of research examining impacts from climate change in the context of other changes.

2

Natural and Human-Caused Influences on Earth's Energy Imbalance

2.1 KEY MESSAGES

Emissions of greenhouse gases from human activities are increasing the concentration of these gases in the atmosphere. Human activities, such as the extraction and burning of fossil fuels, cement and chemical production, deforestation, and agricultural activities, emit greenhouse gases (GHGs)—which include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases)—to the atmosphere.

Total global greenhouse gas emissions continue to increase, even though U.S. emissions of CO_2 have decreased slightly in recent years largely due to changes in energy production and consumption. The United States has the highest cumulative emissions[1] and is among the highest per capita emissions of GHGs in the world. The most recent decade (2010–2019) marked the largest decadal increase in global CO_2 emissions on record. Since 2009, methods of monitoring, observing, and synthesizing inventories of these emissions have improved.

Increased greenhouse gases in the atmosphere are changing Earth's energy balance, which governs the physics and dynamics of the climate system. Earth's climate is regulated by its radiative energy balance—the difference between solar energy absorbed by the surface and atmosphere and infrared energy emitted back to space. GHGs absorb and re-emit infrared radiation (energy) in all directions, including downward to the surface and upwards to space. The overall imbalance (net total of human and natural forcings[2]) has led to warming of the climate system since 1750. Advances in remote sensing, longer term records, and analyses provide continued and more robust support for conclusions about Earth's energy imbalance than was available in 2009.

Multiple lines of evidence show that greenhouse gas emissions from human activities are the primary drivers of the observed long-term warming trend and other changes in Earth's energy balance and that natural forces cannot account for observed changes. No known natural drivers, such as incoming solar radiation or volcanic emissions, can explain observed changes. This is particularly true for the magnitude of warming at Earth's surface and the vertical distribution of warming in the troposphere (lower atmosphere) and cooling in the stratosphere (upper atmosphere). These changes are consistent with the physics and dynamics of the climate response to GHG increases.

[1] Cumulative emissions are the total sum of GHGs released over time. This is usually calculated using 1750, when the industrial revolution began, as a starting point.

[2] Forcings are factors that influence Earth's radiative balance. Human forcings (or "anthropogenic" forcings) consist of the emissions of GHGs and land-use change. Natural forcings are nonhuman factors that affect Earth's radiative balance. This includes factors such as solar radiation, Earth's orbital cycle, and volcanic activity.

Statements from EPA (2009a) continue to be true and are supported by improved scientific evidence. Evidence for human-caused increases in greenhouse gas emissions, their effects on Earth's climate, and the attribution of climate change to human activities has grown stronger and more compelling, backed by multiple, independent lines of improved data and analysis.

2.2 GREENHOUSE GASES AND THEIR EMISSIONS

EPA (2009a) considered six well-mixed GHGs emitted by human activities: CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6 (Box 2.1). Both global and U.S. emissions of GHGs are dominated by those of CO_2. Emissions of other GHGs are often reported as the amount of CO_2 emissions that would produce an equivalent amount[3] of radiative forcing (the imbalance between incoming and outgoing energy in Earth's atmosphere; see Section 2.3) over a 100-year period, which is referred to as carbon dioxide equivalents, or "CO_2e."

In its 2022 assessment, the Intergovernmental Panel on Climate Change (IPCC) (Dhakal et al., 2022) estimated that total global annual emissions of GHGs had increased to approximately 59 billion metric tons CO_2e per year (gigatons per year, Gt/y). During the decade beginning in 2010, the average emissions were 56 Gt/y, which is 9 Gt/y (or 16%) higher than the decade from 2000 to 2009, leading to the greatest decadal growth in atmospheric

BOX 2.1
Legislative Requirements Applying to Greenhouse Gas (GHG) Emissions Regulations

The 2009 Endangerment Finding (see Box 1.1) identified carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) as the primary GHGs emitted by human activities not already covered by the Montreal Protocol (which controls additional GHGs: chlorofluorocarbons [CFCs] and hydrochlorofluorocarbons [HCFCs]). Three of the GHGs identified by the Endangerment Finding—CO_2, CH_4, and N_2O—are vehicle as well as stationary source emissions. In addition to the GHGs identified in the Endangerment Finding, vehicle emissions also include "criteria pollutants"—nitrogen oxides, carbon monoxide, sulfur oxides, and particulate matter—which are associated with direct human health effects.

As recognized in the Endangerment Finding, the Clean Air Act Section 202(a) requires EPA to create emission standards to limit air pollutants that endanger public health or welfare. These regulations focused initially on criteria pollutants but apply also to vehicle GHG emissions. Additionally, the Clean Air Act broadly together with the American Innovation and Manufacturing Act of 2020 require EPA to control stationary source emissions for all GHGs included in the Endangerment Finding.

At the time of the Endangerment Finding, EPA vehicle exhaust emission standards regulating criteria pollutants had been in place for many years. Vehicle CH_4 and N_2O emissions have been subsequently regulated since 2015. Vehicle emission standards for CO_2 are planned to start in 2027. CO_2 emissions have also been regulated indirectly by evolving Corporate Average Fuel Economy standards, administered by the National Highway Traffic Safety Administration since 1975. CO_2 from stationary power plants has recently been regulated by EPA. Two of the gases identified in the Endangerment Finding, HFCs and PFCs, are regulated with stationary source emissions limits, and SF_6 is limited in some cases and required to be reported in others.

[3] Global Warming Potential is a common metric in discussions of GHGs used in EPA (2009a). Global Warming Potential compares how much total heat a GHG traps over a chosen time horizon (e.g., 100 years) relative to CO_2. Carbon dioxide equivalents (CO_2e) express a GHG quantity as the amount of COv that would cause the same trapping of heat over that horizon, calculated as mass multiplied by Global Warming Potential.

concentrations in the modern record. In contrast, over the same period, GHG emissions from the United States have decreased (Figure 2.1). EPA (2009a) used the latest data available at the time (from 2007) to estimate U.S. emissions as 7.150 Gt/y of CO_2e. Since that time, improvements in the emission estimation procedures used by EPA facilitated a refining of the estimate of 2007 emissions to 7.530 Gt/y CO_2e (EPA, 2024a). Estimated emissions for 2022, the latest year for which EPA has developed a comprehensive national emission estimate, are 6.343 Gt/y CO_2e. This decrease in total emissions is largely the result of changes in the relative amounts of different energy sources used in the United States.

Since 2007, the United States has transformed from an energy importing country to the world's largest producer of oil and natural gas and a major exporter of energy. Major trends with consequences for GHG emissions include widespread substitution of coal used for electricity generation with natural gas and renewable sources of energy and increases in the efficiency of petroleum use for transportation (Figure 2.2). The changes in electricity generation have led to decreases in CO_2 emissions because burning coal results in higher emissions of CO_2 per unit of energy produced than burning natural gas or using renewable sources of energy.

Improvements in the fuel efficiency of vehicles and introduction of electric vehicles has led to a relatively constant to slightly decreasing amount of petroleum use, despite increases in total miles travelled by vehicles in the United States (U.S. Bureau of Transportation Statistics, 2025). While total emissions in the United States have decreased due to these changes in patterns of energy use, the country still remains one of the largest sources of GHG emissions both in total and per capita, and the largest cumulative emitter of GHGs (IPCC, 2022b; Jones, Peters et al., 2024).

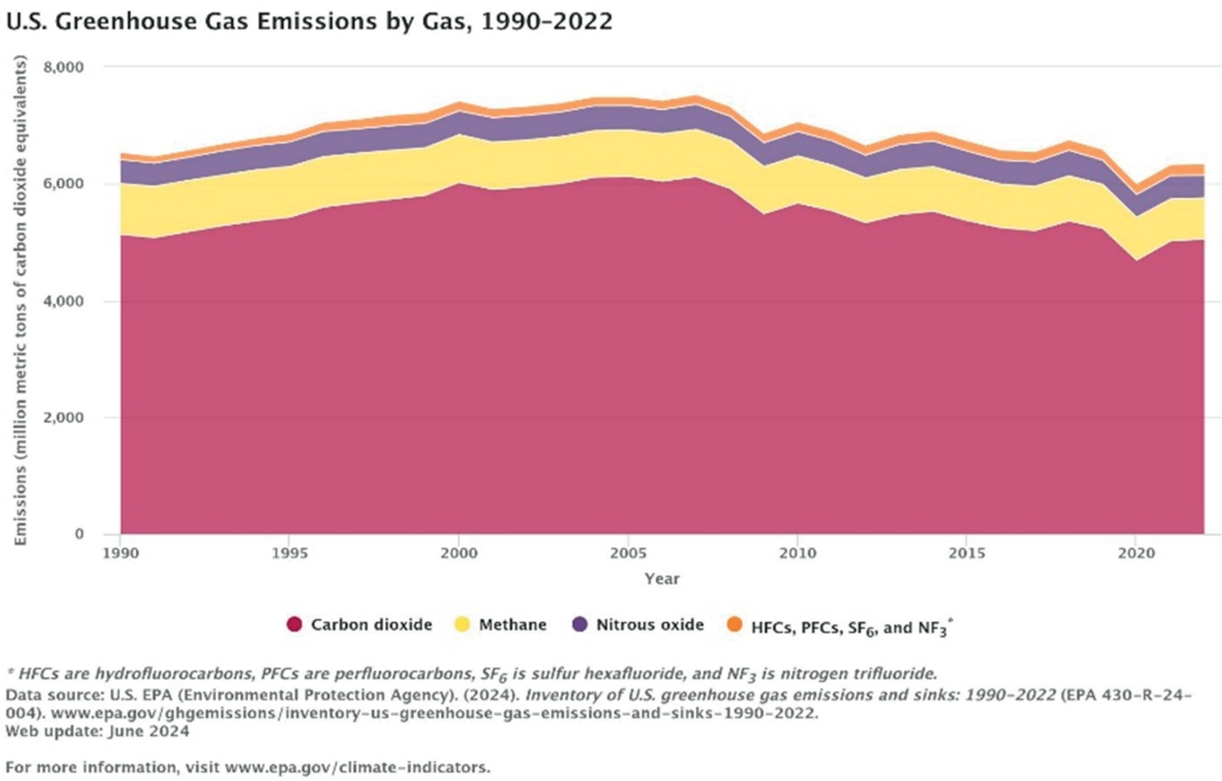
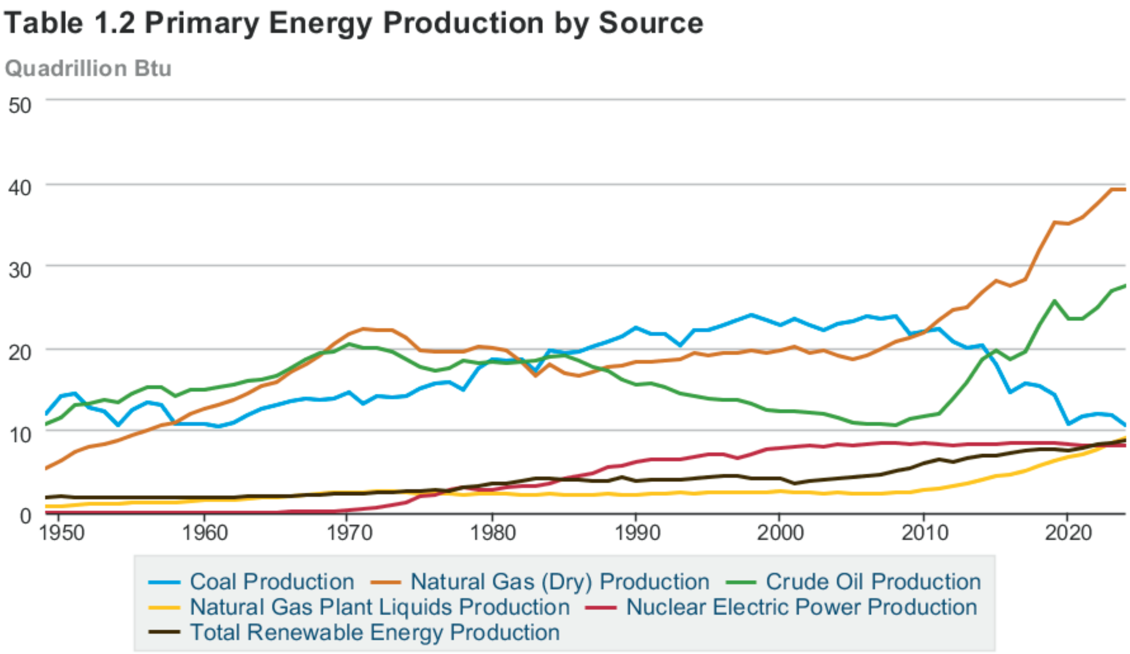


FIGURE 2.1 Emissions of CO_2, CH_4, N_2O, and several fluorinated gases (HFCs, PFCs, SF_6, and NF_3) in the United States from 1990 to 2022. Data: EPA, 2024a.
SOURCE: EPA, https://www.epa.gov/climate-indicators/climate-change-indicators-us-greenhouse-gas-emissions. Accessed September 2025.



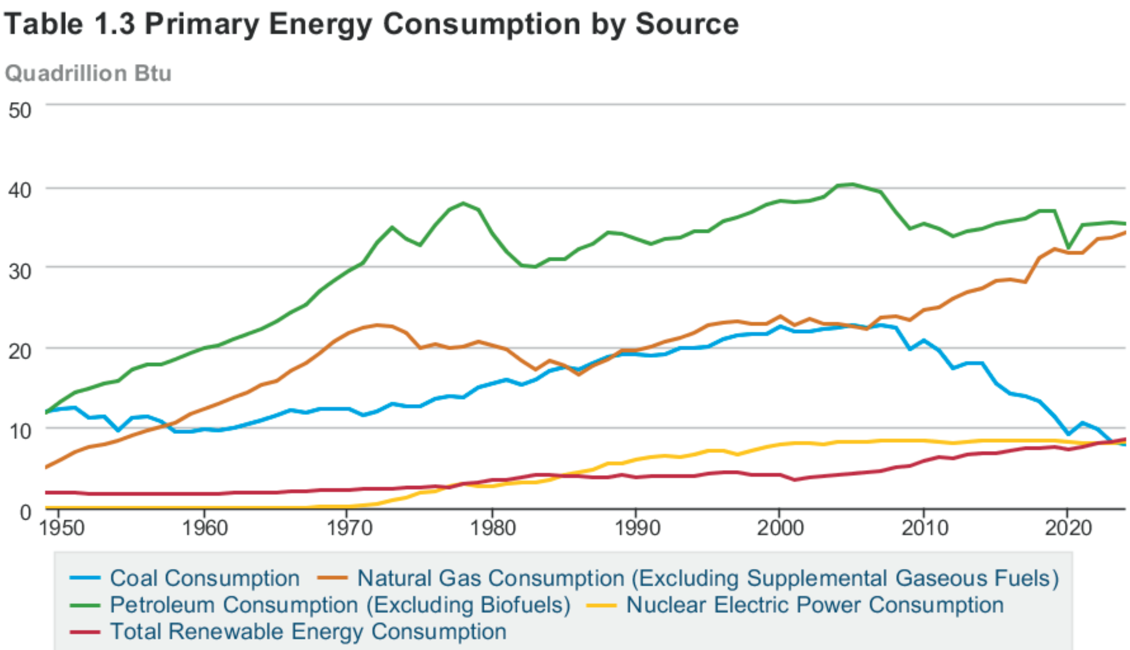


FIGURE 2.2 U.S. energy production from 1990 to 2025 (top) and consumption (bottom). The production and use of energy in the United States have evolved since 2007, as tracked by the U.S. Department of Energy's Energy Information Administration (EIA).
SOURCES: EIA, 2025a, 2025b.

Changes in energy use have also affected emissions other than GHGs. EPA (2009a) noted that emissions of sulfur dioxide (SO_2) and particulate matter (particles less than 10 microns in diameter, PM_{10}), which accompany the burning of fossil fuels, had decreased in the decades prior to 2009. SO_2 emissions have continued to decrease since 2009 due to shifts away from the use of coal in electricity generation and the lowering of the sulfur content in fuels in diesel-fueled vehicles. As reported through EPA's National Emissions Inventory,[4] emissions of SO_2 decreased from 16.3 million tons per year in 2000 to 8.0 million tons per year in 2009 (EPA, 2025a). From 2010 to 2020, total emissions were further reduced to 1.8 million tons per year. These decreasing emissions in SO_2 led to reduced formation of sulfates found in particulate matter in the atmosphere. Because sulfates in particles have a net cooling effect, the reduced sulfate concentrations would be expected to lead to reduced cooling.

Direct emissions of particulate matter, not including those associated with wildfires, are more complex, having decreased by approximately one-third from 2000 to 2009 then having remained relatively constant since. The quantity of particulate matter emissions from wildfires varies widely from year to year. For example, in 2022, a year which had large areas burned by wildfires, PM_{10} emissions from wildfires were estimated to be an order of magnitude larger than in 2009. The wildfire emissions in 2022 occurred in localized areas for limited time periods but were estimated to increase total national PM_{10} emissions for the year by roughly 20%, resulting in very high concentrations of PM_{10} during the time periods when the fires were occurring (EPA, 2025h).

Estimates of emissions of GHGs and other pollutants have differing levels of associated uncertainty in available data and methodologies. Among GHGs, estimates of CO_2 emissions have the lowest uncertainties because the majority of these estimates are based on fuel consumption data, which are accurately and precisely tracked, multiplied by the emissions per usage, which is also well-known. Estimates of emissions of other GHGs, such as CH_4, have higher uncertainties, but these uncertainties have been reduced by advances in measurement technologies over the last decade (NASEM, 2018). In reviewing the status of CH_4 emission measurements, the National Petroleum Council (2024) concluded in a report to the U.S. Secretary of Energy that "new measurement technologies have emerged over the last five years that are dramatically improving emission detection and the accuracy of emission estimates" (p. 3-1).

Observations of atmospheric concentrations provide additional evidence of increasing global GHG emissions. Concentrations of GHGs in the lower atmosphere, such as those measured at the Mauna Loa monitoring station in Hawaii, are increasing (Figure 2.3). Figure 2.4 shows annual increases in N_2O concentrations, which have been increasing at a generally accelerating rate, and CH_4 concentrations, for which emission increases have had more complex behavior but overall have been increasing at a generally accelerating rate since 2009.

The most recent average decadal increase in CO_2 concentration is more than 2 parts per million (ppm) per year. This rate of increase is more than 100 times faster than natural increases, such as those that occurred at the end of the last Ice Age 11,000–17,000 years ago. Further documentation of increases in atmospheric GHG emissions comes from the relative abundance of carbon isotopes in the observations. Measured decreases in the fraction of the carbon isotopes ^{14}C and ^{13}C in ice core records show that the rise in CO_2 is largely from combustion of fossil fuels, which have low ^{13}C fractions and no ^{14}C (NRC, 2020; Figure 2.7, top). Figure 2.5 shows these longer historic trends combined with observations from recent atmospheric concentrations, which demonstrate the steep rate of increase beginning in approximately 1750. Beyond these historical records, fundamental physical and chemical processes also indicate that once emitted, CO_2 persists in the atmosphere for centuries,[5] ensuring today's emissions will contribute to atmospheric concentrations far into the future.

2.3 EARTH'S ENERGY IMBALANCE

Understanding how energy flows through the Earth system, quantifying those flows in the form of energy fluxes, and evaluating the factors that influence and change these fluxes are the foundation for understanding the physical climate system and are the basis for characterizing and predicting changes to Earth's climate. Changes in energy flows, referred to as "forcings," operate on a variety of timescales and can be human-caused or from natural

[4] See https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei.
[5] For more information about the global carbon cycle, see "Global Carbon Budget 2024" (Friedlingstein et al., 2025).

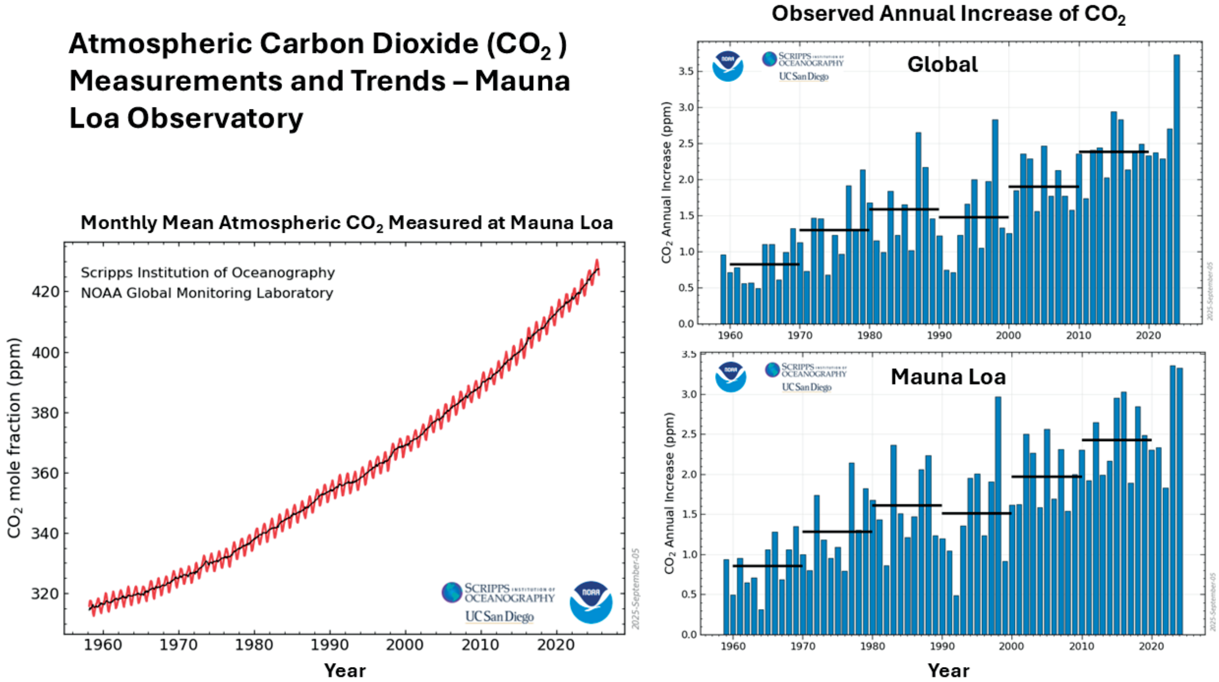


FIGURE 2.3 Atmospheric CO_2 measurements and trends from Mauna Loa Observatory. These graphs compare the rise of atmospheric CO_2 measured at Mauna Loa (Left: monthly mean 1960–2025; Right [bottom]: annual average increase) and global records (Right [top]: global annual increase from the Global Greenhouse Gas Reference Network[1]). The decadal average rate of increase of CO_2 in the graphs on the right is depicted by the black horizontal lines. Rates of increase measured at Mauna Loa align closely with global records.

[1] The Global Greenhouse Gas Reference Network is based in NOAA's Global Monitoring Laboratory and uses observations from observatories, aircore samples from ballons, and air samples taken by small aircrafts and volunteers.

SOURCE: NOAA, 2024.

sources. The influence of any individual forcing is typically compared using a measure of its impact on the Earth's radiative balance, measured as the annual average net change in radiation (in Watts) at the top of the atmosphere per square meter of the planet's surface (W/m^2).

Since 2009, advances in observations and the analysis of expanding time series have shown that Earth has a positive energy imbalance—i.e., more energy is coming in than going out—and this imbalance is increasing over time (Hakuba et al., 2024; Loeb et al., 2021). Over the longer-term, this imbalance will drive additional net heating of the planet. Human-caused, or anthropogenic, forcings are the primary driver of the imbalance in Earth's energy and resulting heating. Total anthropogenic forcing comes mainly from GHG emissions from human activities but also includes contributions from aerosols (particulates that are mostly cooling agents) and changes in the Earth's surface cover. Combining all of these human-caused contributions leads to a best estimate of +2.97 (+2.05 to +3.77) W/m^2 in net total anthropogenic radiative forcing for 1750 to 2024 (Forster et al., 2025). This estimate has increased by more than 80% since the estimate cited in EPA (2009a); the net total anthropogenic forcing for 1750 to 2005 was +1.6 W/m^2 (+0.6 to +2.4 W/m^2).

Observations of Earth's Energy Imbalance

The international community has developed a robust and comprehensive understanding of Earth's energy balance, along with its associated uncertainties, through decades of careful and sustained assessments (e.g., Stephens et al., 2022). Today, more objective methodologies that jointly constrain both the water and energy budgets are

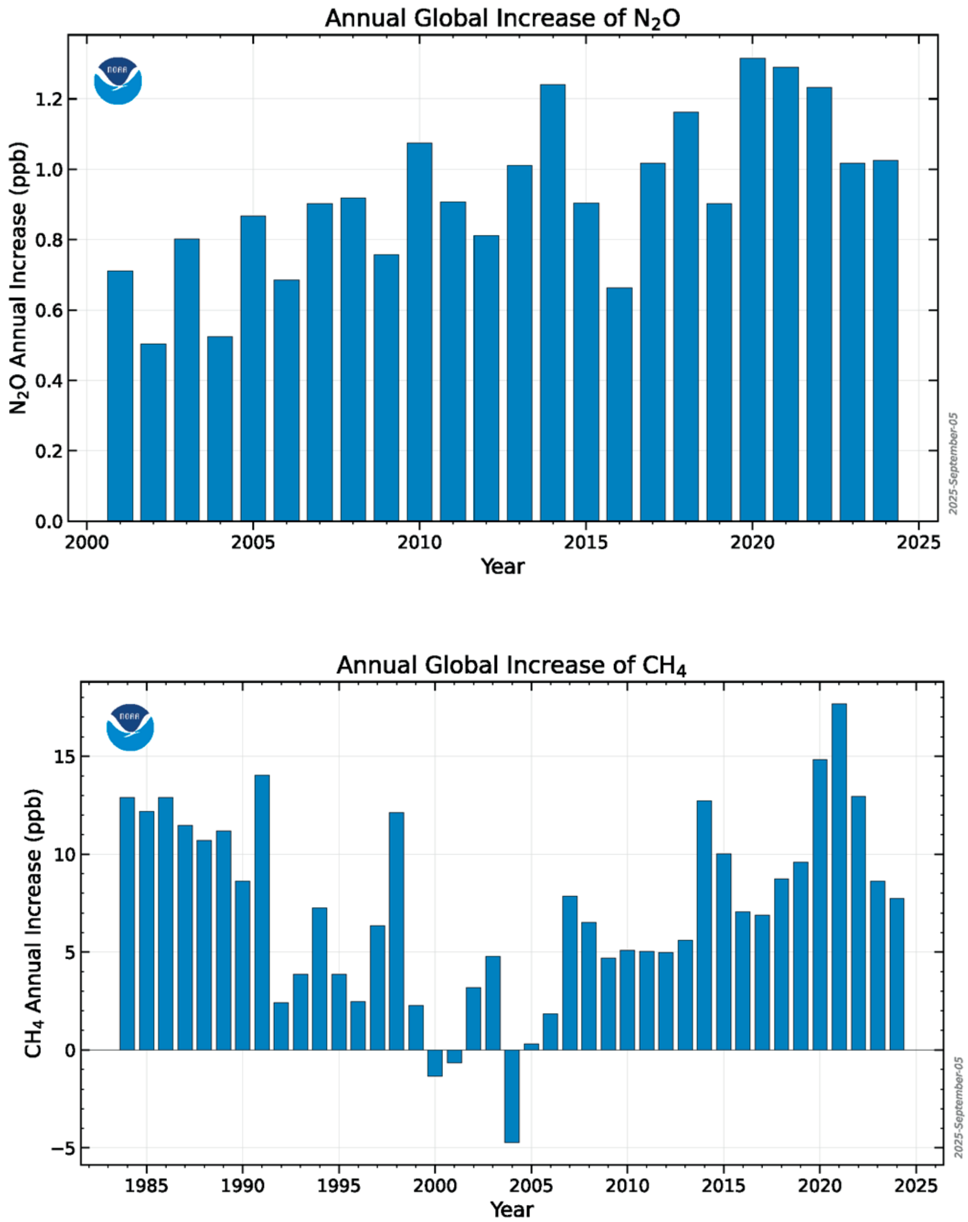


FIGURE 2.4 Annual increases in atmospheric nitrous oxide (N_2O; top) and methane (CH_4; bottom) based on globally averaged marine surface data. The baseline annual atmospheric concentration (0 line) of N_2O in 2001 is 316.36 parts per billion (ppb) (top) and of CH_4 in 1984 is 1644.84 ppb (bottom).
SOURCE: Lan et al., 2022.

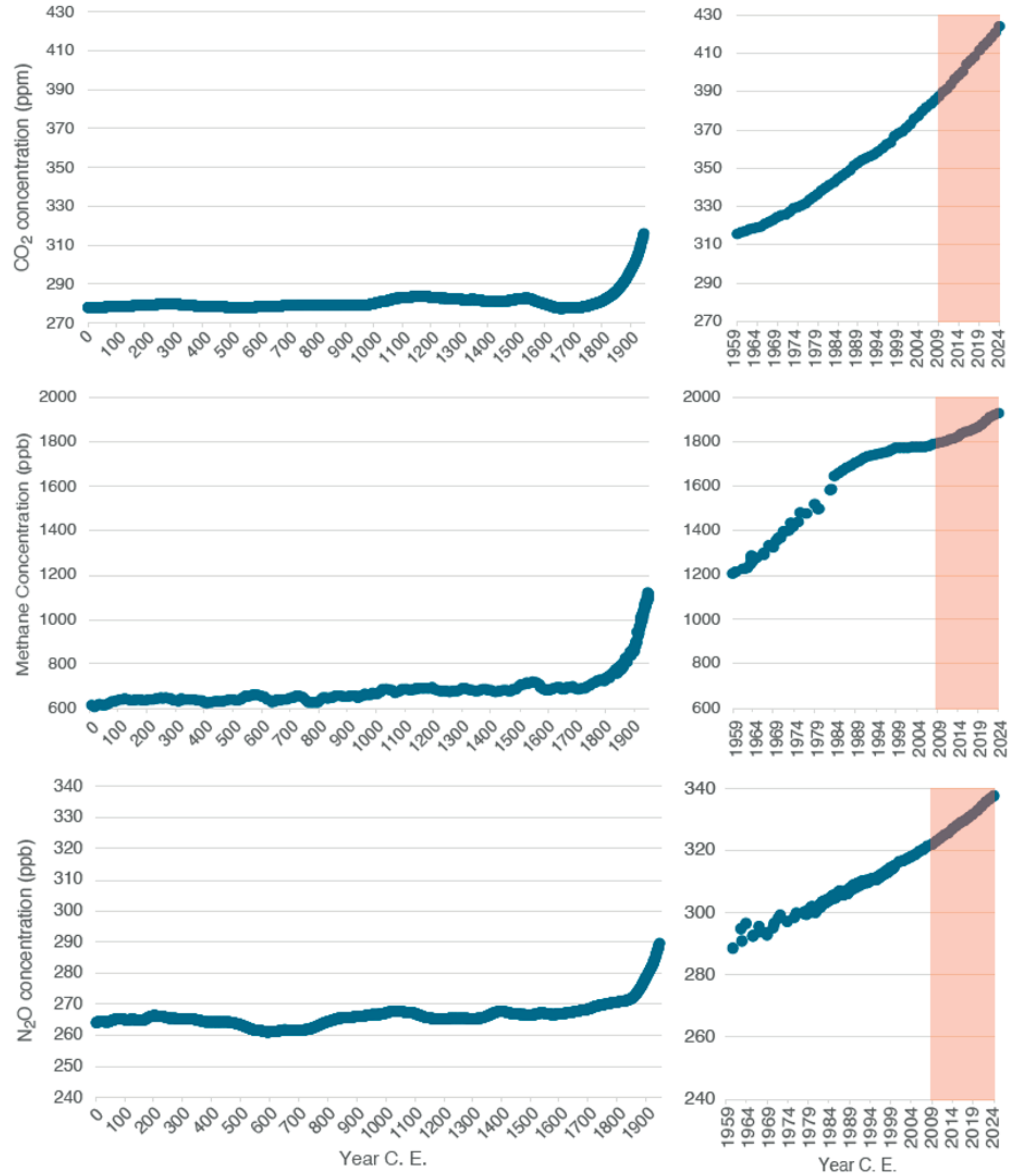


FIGURE 2.5 Global concentrations of the primary human-caused greenhouse gases over the last approximately 2,000 years (blue dotted lines), with the shaded areas (orange) indicating the time period since EPA (2009a) was published. The timescale (x-axis) for the left panel spans 2,000 years; the timescale for the right spans only the past 65 years.
SOURCES: Data in the left panels are from ice cores (Ahn, 2023) while data in the right panels are from NOAA observations (Lan et al., 2022; NOAA Global Monitoring Laboratory, n.d.).

used (L'Ecuyer et al., 2015; Rodell et al., 2015), moving away from prior, more ad hoc, methods used at the time of EPA (2009a). These methodologies support the finding that Earth, in the annual mean, currently experiences a radiative imbalance at the top of the atmosphere, referred to as Earth's Energy Imbalance (EEI). While net radiative forcing represents the combined effect of external drivers of Earth's energy balance, EEI is the portion of the forcing not yet offset by the planet's radiative response and observed directly as the annual mean of Earth's heat uptake. EEI is measured as the sum of all heat content changes occurring in the ocean, land, atmosphere, and cryosphere. EEI is the most holistic picture to date of heat accumulation by the Earth system and a quantitative measure of the cumulative impact of both natural and anthropogenic radiative forcings and feedbacks. Independent estimates of the heat uptake, taking account of all heat content changes, largely match estimates of EEI (Hakuba et al., 2024; Meyssignac et al., 2019; von Schuckmann et al., 2016) (see Figure 2.6).

Approximately 90% of Earth's heat uptake occurs in the ocean. Hakuba et al. (2024) offer a comprehensive review of 18 different sources of ocean heat content data and conclude that the range of annual mean EEI falls between 0.40 to 0.96 W/m^2 where the spread is due to differing sources of ocean data, mapping methods, and quality control procedures across ocean data products (Figure 2.6). They also assess the rate of change of EEI over the observation record and, while ranging from 0.1 to 1.0 W/m^2 per decade, conclude that all major sources of data indicate an increasing rate of EEI over the past approximately 20 years. This pattern points to an accelerating warming of the planet (e.g., Mauritsen et al., 2025), which is also consistent with observations that suggest an accelerated rise in sea level due in part to thermal expansion of sea water (see also Section 3.5).

EEI methods and estimates provide more robust support for the EPA (2009a) conclusion that "the global average net effect of the increase in atmospheric GHG concentrations, plus other human activities (e.g., land-use change and aerosol emissions), on the global energy balance since 1750 has been one of warming" (p. ES-2).

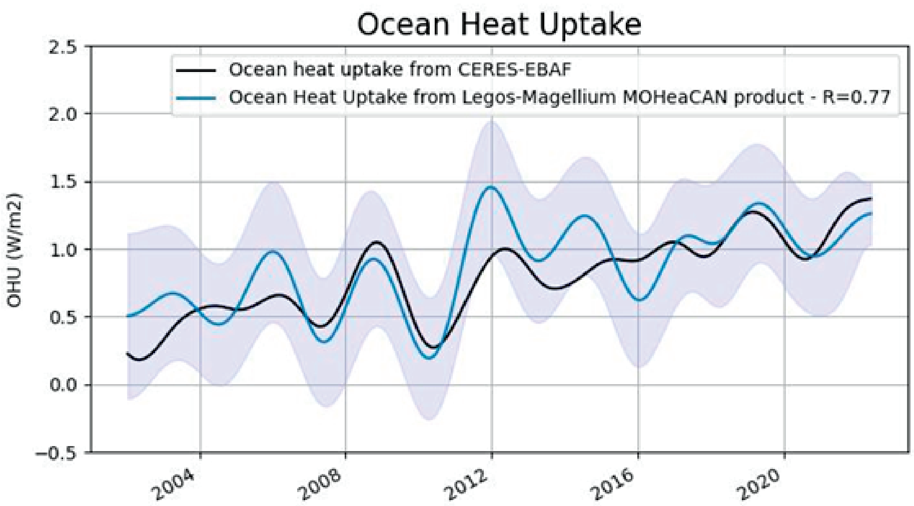


FIGURE 2.6 The Monitoring Ocean Heat Content and earth energy imbalANce (MOHeaCAN) (Legos) time series of ocean heat uptake (OHU, visualized in blue) and the 90% confidence interval of the Clouds and the Earth's Radiant Energy System Energy Balanced and Filled (CERES EBAF) net radiative flux (EEI, visualized in black). Both time series are low-pass filtered at 3 years cut-off time (Lanczos), which removes high-frequency noise related to intrinsic ocean variability. Legos ocean data and CERES Top of Atmosphere (TOA) radiative flux data broadly agree that the Ocean Heat Uptake is increasing over time. SOURCE: Hakuba et al., 2024. CC BY 4.0.

Natural Forcings on Earth's Energy Imbalance

Over timescales of decades to centuries, the most important known natural forcings are solar output and volcanic eruptions. Prior to modern measurement techniques, estimates of long-term changes in the output of the Sun have substantial uncertainties. Nevertheless, solar forcing from the preindustrial average over the ~11-year solar cycle to the average over the last complete solar cycle (2009–2019) is estimated by the IPCC's Sixth Assessment Report and more recent analyses (Forster et al., 2025) to be +0.01 W/m^2 (–0.06 to +0.08; 90%[6] confidence interval). The best estimate of solar forcing is roughly 300 times less than anthropogenic forcing. Even the high end of the range of solar forcing is equal to only a few percent of anthropogenic forcing over this period. Uncertainties in observations since the preindustrial period do not support conclusions about trends in solar forcing over that period. However, over the last approximately 45 years, for which satellite observations are available (leading to higher confidence in the observed trends), it is very likely that solar forcing has decreased (Amdur and Huybers, 2025; Matthes et al., 2017; Montillet et al., 2022). This likely decrease in solar forcing was observed at the same time that the Earth has been warming at its most rapid pace since the preindustrial period.

Volcanic forcing is highly irregular and sporadic, with large eruptions that inject material into the stratosphere driving short-term cooling but with no evidence for long-term trends over the last two centuries (Forster et al., 2021). CO_2 emissions from volcanoes are negligibly small. Hence, natural forcing is both very small over the time since industrialization and has very likely caused a minor amount of cooling over recent decades rather than contributing to the observed warming.

Radiative Forcing of Greenhouse Gases

Owing to the successful implementation of the Montreal Protocol (1987 international treaty to control ozone-depleting substances), concentrations of several fluorinated GHGs (CFCs) have decreased, whereas concentrations of other fluorinated gases are still increasing (i.e., CFC-replacements, such as hydrofluorocarbons and the industrial PFCs) (Forster et al., 2025). The 2024 estimate of radiative forcing relative to the 1750 baseline[7] from halogenated gases (primarily fluorine-containing, or F-gases) is +0.41 (+0.33 to +0.49) W/m^2 (Forster et al., 2025), with relatively flat growth rates owing to the offsetting influence of declining CFCs and increases in other F-gases. These gases are entirely anthropogenic in origin.

CO_2 concentrations have increased by ~50% (through 2023) relative to the mean of the range seen from 1000 to 1850, with analogous increases of ~160% and 25% for CH_4 and N_2O, respectively (Figure 2.5). The observed concentration increase in these gases is attributable almost exclusively to anthropogenic activities based on analyses of budgets for each GHG and on the isotopic signature of atmospheric carbon (see Figure 2.7). Current CO_2 levels are likely the highest they have been in the last 3 million years (Canadell et al., 2021; de la Vega et al., 2020; Martínez-Botí et al., 2015), and the rates of change in all three of the main GHGs (CO_2, CH_4, and N_2O) are faster than those seen at any time in the last million years of ice core records (Canadell et al., 2021).

Understanding of the effect of GHGs on the Earth's energy balance remains solidly grounded in physics and in laboratory measurements, which date back to the 19th century (e.g., Tyndall, 1863), as well as in surface and satellite measurements (e.g., Harries et al., 2001; Teixeira et al., 2024). This understanding of the fundamental physics of the Earth's energy system, combined with observational constraints on feedback[8] processes, mean that at the global scale the effect of a GHG forcing can be evaluated with a simple equation and does not require the use of complex numerical models or other complicated analyses. In practice, relatively simple models used decades ago can now be seen to have performed extremely well in matching the observed global mean warming over time per unit radiative forcing (Hausfather et al., 2020; Supran et al., 2023).

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[6] The range in parentheses included with radiative forcing estimates represents the "very likely" range, meaning there is a 90% likelihood that the actual value falls within this range.

[7] Unless otherwise specified, estimates of radiative forcing (W/m^2) are given relative to a preindustrial (1750) baseline.

[8] Feedbacks are natural or human-induced processes that impact a system (i.e., hydrologic, climate, atmospheric). Positive feedback amplifies the initial change, and negative feedback decreases the initial change.

Since EPA (2009a), the radiative forcing due to increasing atmospheric concentrations of the three main human-caused GHGs has increased from the +2.30 (+2.07 to +2.53) W/m^2 estimate in 2005 to +3.13 (+2.7 to +3.6) W/m^2 in 2024 (Forster et al., 2025). This rapid rise in forcing continues the trend reported in EPA (2009a) that "the rate of increase in positive radiative forcing due to these three GHGs during the industrial era is very likely to have been unprecedented in more than 10,000 years" (p. ES-2).

Though not emitted directly by anthropogenic activities, ozone is another important GHG. Ozone in the lower atmosphere (the troposphere) has a large warming impact on climate, especially in the upper troposphere. Ozone in the upper atmosphere (the stratosphere) has only a weak effect on climate but is important in protecting the surface from ultraviolet radiation. Tropospheric ozone has increased since industrialization due to human-caused emissions of ozone precursor gases that lead to photochemical ozone production. The effect of this tropospheric ozone increase has outweighed the impact of ozone loss in the stratosphere, leading to a net positive forcing of +0.50 (+0.25 to +0.75) W/m^2 in 2024 (Forster et al., 2025). Importantly, roughly half the radiative forcing from tropospheric ozone increases is due to emissions of CH_4, which contributes to the chemical formation of ozone in the troposphere. Hence, the overall climate influence of the three main GHGs is larger than that attributed to changes in their concentrations alone.

Non-GHG Radiative Forcing: Aerosols

Aerosols affect radiative forcing both through direct influences on radiation and indirect effects on cloud microphysics and lifetime, which impact the radiative properties of clouds. The IPCC's Sixth Assessment Report (IPCC, 2021) provides an updated assessment of this combined aerosol forcing. Forster et al. (2021) conclude with high confidence[9] that the radiative forcing from aerosols is negative (cooling) and estimate, with medium confidence, that for 2019 it is −1.1 (−1.7 to −0.4) W/m^2; the total effective radiative forcing from aerosols in 2024 is estimated to be −1.07 (−1.90 to −0.43) W/m^2 (Forster et al., 2025). This aerosol forcing (about −1 W/m^2) does affect the energy balance, although the cooling effect is only about a quarter of the warming associated with GHGs (about +4 W/m^2 from combined CO_2, CH_4, N_2O, ozone, and F-gases forcings included above) over the Industrial Era.

2.4 ATTRIBUTION OF EARTH'S WARMING AND ENERGY IMBALANCE TO HUMAN ACTIVITIES

As stated in EPA (2009a), "[GHGs], once emitted, can remain in the atmosphere for decades to centuries, meaning that (1) their concentrations become well-mixed throughout the global atmosphere regardless of emission origin, and (2) their effects on climate are long lasting" (p. ES-1). Atmospheric concentrations of the three main GHGs—CO_2, CH_4, and N_2O—have continued to increase since 2009 as discussed in the previous sections, and it is virtually certain that this increase is due to human activities. These resulting concentration increases in the atmosphere represent human-forcing on Earth's energy balance. The increased concentrations of well-mixed GHGs impact the climate though the increased infrared radiation they emit. This enhanced emission downward to the surface is an expression of the GHG radiative forcing and drives the surface and lower atmospheric warming. The enhanced emission of infrared radiation upward to space, by contrast, results in a cooling of the upper atmosphere. This warming-cooling dipole pattern, a unique signature of GHG radiative forcing of Earth's climate, is well documented in observations of temperature change (Santer et al., 2023).

No known natural process could account for observed increases in GHGs that both (1) are well beyond the range of values seen over the past million years and (2) occur simultaneously for all three of the main well-mixed GHGs. Furthermore, the isotopic record of CO_2 (Figure 2.7, top) shows an increase in very old, plant-based CO_2 (depleted in ^{13}C) that is a signature of fossil fuel burning (Graven et al., 2020). Consistent with the attribution

[9] When referencing IPCC assessments, statements that include likelihood or confidence levels follow the same established scales used by those authors—e.g., for likelihood: "virtually certain" equates to 99–100% probability; very likely equates to 90–100%; likely equates to 66–100%, etc. For confidence, "very high confidence" refers to at least a 9 out of 10 chance of being correct and "high confidence" to at least 8 out of 10. For more information on these designations, see IPCC (2023).

of increasing GHG concentrations to human activities, and based on understanding of the radiative forcing of different climate drivers and the strength and speed of the climate response to forcing, the best estimate of the anthropogenic contribution to the observed surface warming of 2.23°F (1.24°C; 2 to 2.43°F/1.11 to 1.35°C) for 2015–2024, relative to 1850–1900, is 100% (Eyring et al., 2021; Forster et al., 2025; Gulev et al., 2021). Natural forcings are estimated to have contributed only about 0.09°F (0.05°C; –0.18 to 0.36°F/–0.1 to 0.2°C) to this warming (Eyring et al., 2021), which is higher than the contribution typically found when using the standard practice of comparing periods that both occur at solar minima to avoid the decadal fluctuations of the ~11-year solar cycle.

The observed vertical pattern of warming (lower atmospheric warming [Figure 2.7, middle], upper atmospheric cooling [Figure 2.7, bottom]) is consistent with the effect of increasing GHGs but is inconsistent with the effect of increased solar forcing (Casas et al., 2023; Santer et al., 2023). Thus, it is virtually certain that observed warming is due to human activities (Figure 2.7).

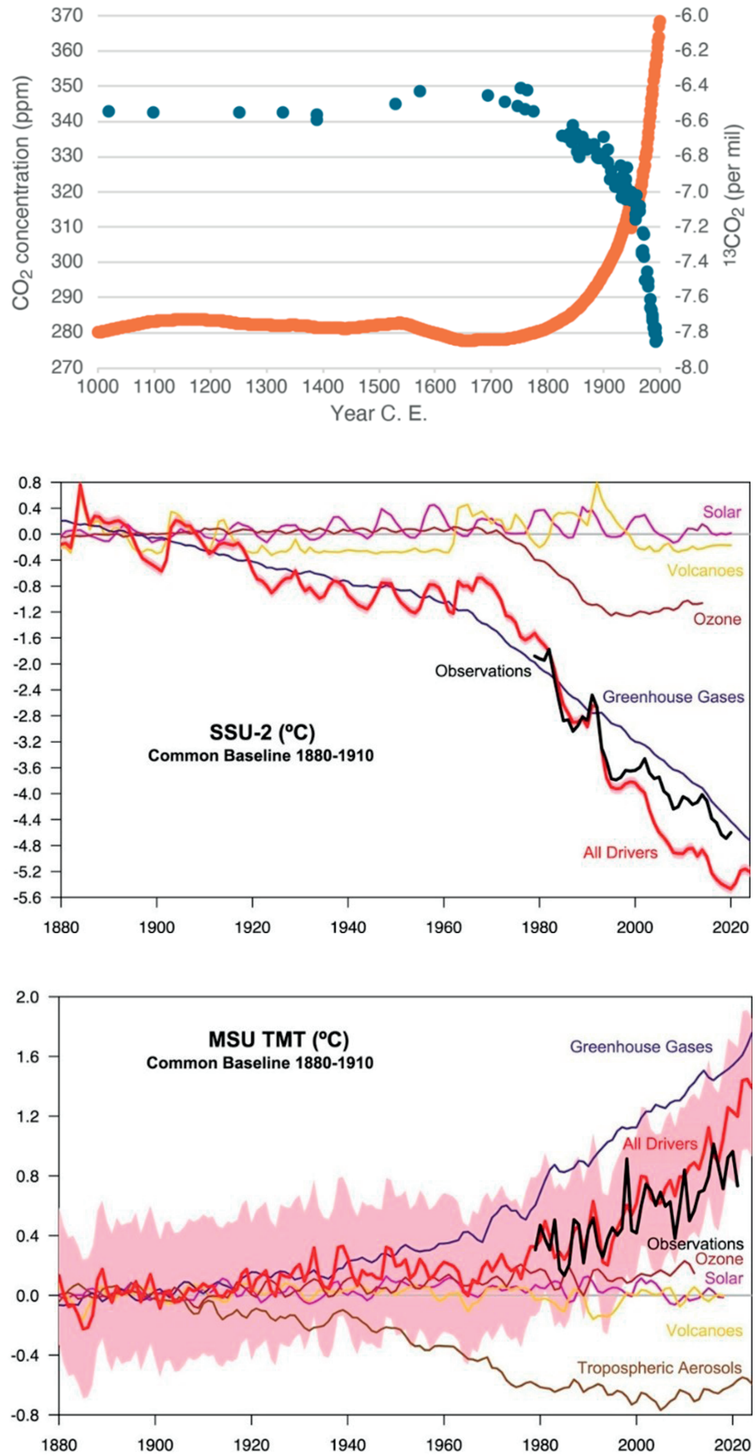


FIGURE 2.7 (Top) Concentration of CO_2 (orange dots, increasing) alongside the fraction of CO_2 containing the ^{13}C isotope (blue dots, decreasing) over the last 1,000 years. Total CO_2 data in the upper panel is from Ahn (2023) and NOAA observations (NOAA Global Monitoring Laboratory, n.d.) with ^{13}C data from Rubino et al. (2019). (Middle and bottom) Observed (thick black lines) and modeled trends (other lines) in atmospheric temperatures in the stratosphere (upper atmosphere cooling, middle figure) and in the middle troposphere (lower atmosphere warming, bottom figure). The lower panels are reprinted with permission from Casas et al. (2023), with observations from the Stratospheric Sounding Unit (SSU) updated from Zou and Qian (2016) and observations from the Microwave Sounding Unit (MSU) updated from Mears and Wentz (2016).

3

Observed Climate Changes from Human-Caused Greenhouse Gas Emissions

3.1 KEY MESSAGES

Improved observations confirm unequivocally that greenhouse gas emissions are warming Earth's surface and changing Earth's climate. Longer records, improved and more robust observational networks, and analytical and methodological advances have strengthened detection of observed changes and their attribution to elevated greenhouse gases (GHGs). EPA (2009a) provided evidence for a range of observed changes in Earth's climate associated with elevated global concentrations of GHGs. Many of the global trends could also be observed in the United States.

Observations show continuing increases in hot extremes alongside declines in cold extremes, furthering the conclusion in EPA (2009a). Six decades of observations document a tripling of average annual heat-wave frequency since the 1960s. Heat metrics in many regions show heat-related changes. For example, occurrence of the hottest day, warmest night, warm spells, and other heat events have intensified in the southeast.

In the United States, regional shifts in annual precipitation and a higher number of extreme single-day precipitation events have been observed. The amount of land area experiencing greater than normal annual precipitation totals has increased since 1895, and the prevalence of extreme single-day precipitation events has risen substantially since the 1980s. Regionally, the Northeast has experienced about a 60% increase in the amount of precipitation falling on the heaviest 1% of days since 1958, with the Midwest up roughly 45% over similar periods.

Observations show continued warming of the Earth's oceans. An increase in global sea surface temperature has been observed since 1900 and ocean heat content increases in the upper 2,000 meters are also evident since 1960 throughout the global oceans. Ocean warming has contributed to increases in rainfall intensity, rising sea levels due to thermal expansion, the destruction of coral reefs, declining ocean oxygen levels, and declines in ice sheets, glaciers, and ice caps in the polar regions.

Ocean pH has decreased, and along with ocean warming, poses risks to marine ecosystems and the benefits they provide. Ocean pH decreased from 8.2 in 1750 to 8.1 today, consistent with the finding in EPA (2009a), and represents about a 30% increase in the hydrogen ion concentration in ocean water (which equates to less alkaline and more acidic conditions). Changes in pH in U.S. offshore waters track with the global average trends, but changes in U.S. coastal waters vary due to local conditions. Decreasing ocean pH, along with warming, poses risks to species with shells and skeletons and coral reefs.

Global mean sea level has risen about 7 inches (approximately 18 centimeters) since 1900, and the rate of sea level rise is accelerating. Regional relative sea level rose on average by approximately 11 inches in the last century along the continental United States, putting many coastal communities at risk of increased coastal flooding and vulnerability to coastal storms. Changes in average sea level have doubled the frequency of high tide flooding in the continental United States over the past few decades.

Evidence of increasing wildfire severity linked to climate change has grown since EPA (2009a). Changing climate conditions, including warmer springs, prolonged summer dry periods, and drier soils and fuel sources, have increased the likelihood for wildfire ignition and spread. The total area burned per annum by wildfires in the western United States has increased in recent decades, resulting in substantial increases in fine particulate matter and other air pollutants.

The following sections provide more detail on the observed changes of key Earth system components—temperature, precipitation and drought, oceans, cryosphere, and biosphere—since EPA (2009a), including attention to trends, extremes, and regional variation across the United States, as well as signals of human attribution to these observations.

3.2 TEMPERATURE

The Earth energy imbalance discussed in Chapter 2 leads to warming of the surface and lower atmosphere, which is clearly detected in temperature observations. Global mean surface temperatures have increased by 2.23°F (1.24°C; ranging[1] 2.00 to 2.43°F/1.11 to 1.35°C) for approximately the last decade (2015–2024) relative[2] to average (Forster et al., 2025). This temperature increase is approximately 60% greater than the warming reported in EPA (2009a), reflecting the very rapid warming of the planet during the last two decades. The warming rate reached a value of 0.49°F (0.27°C; 0.36 to 0.72°F/0.2 to 0.4°C) per decade during 2015–2024, helping drive warming rates over the past 50 years and decadal average temperatures both to their highest values in at least the last 2,000 years (Forster et al., 2025; Gulev et al., 2021).

Consistent with global trends, temperatures in the United States have increased and at an increasing rate (Figure 3.1). Because the land warms more than the ocean, the U.S. annual mean has increased more than the global mean. Since 1970, annual mean temperatures in the contiguous United States have increased by 2.5°F (1.4°C) and by 4.2°F (2.3°C) in Alaska (Marvel et al., 2023) compared to the global mean of approximately 1.7°F (0.9°C). This is a marked increase from the 1.3°F (0.7°C) U.S. temperature increase reported in EPA (2009a) for the 20th century, continuing the trend of the rate of warming increasing, in addition to the actual temperature increase, over the past (now more than four) decades.

Warming has been observed nationwide but is the most pronounced in Alaska, the West, and the Northeast. The Southeast has historically experienced slower warming (called a "warming hole," where long-term temperature trends are negative or non-significant compared to the rest of the country), but this trend has diminished in recent decades. The United States has also experienced longer summers and shorter winters, with winters warming nearly twice as fast as summer in many northern states. Night temperatures have also increased consistently in both summer and winter, which affects plants and ecosystems (see Chapter 6). Temperature trends are observed and supported by instrumental surface networks and homogenized datasets; homogenization[3] has improved and high-resolution reanalyses have sharpened the detection of regional trends since 2009 (Eyring et al., 2021; Marvel et al., 2023).

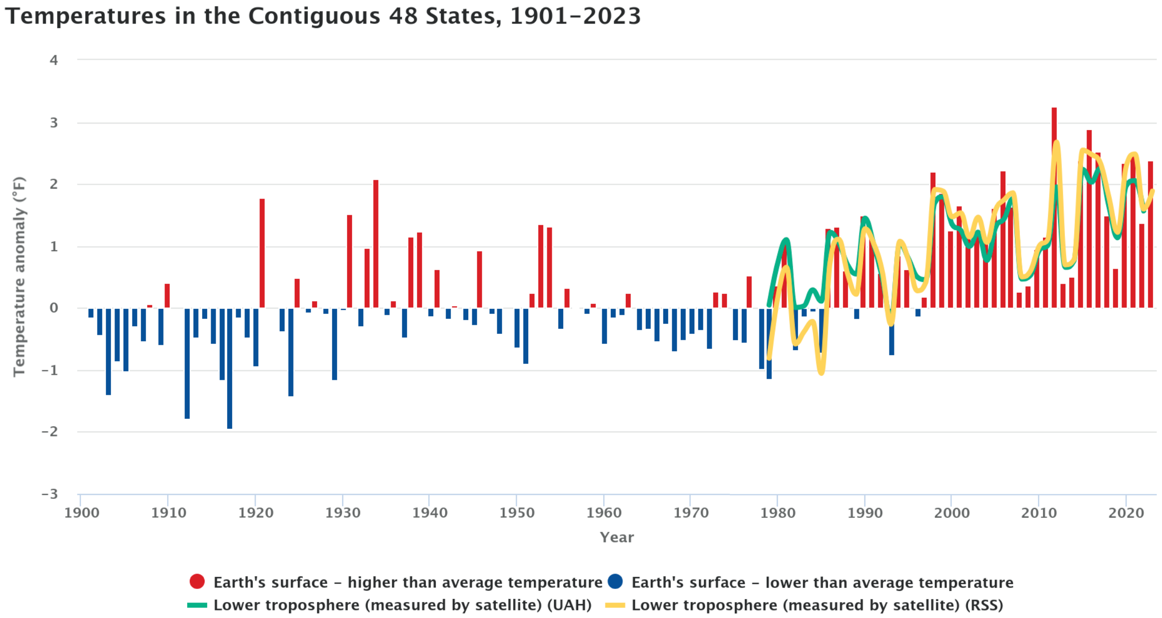
Extreme Temperatures

Observations show continuing increases in hot extremes alongside declines in cold extremes since 2009, furthering the conclusion in EPA (2009a) that "widespread changes in extreme temperatures have been observed

[1] Temperature ranges provided in parentheses represent the "very likely" or 90% confidence interval.

[2] Many estimates in Chapter 2 used 1750 as a baseline; however, quantities provided in this chapter vary in baseline depending on what characteristic is being measured and the start of long-term observational records for that characteristic. These baselines are provided as appropriate for different observations.

[3] Homogenized datasets adjust for non-climatic influences; for example, station moves or instrument changes, to ensure observed trends reflect real changes rather than artifacts of data collection methods.



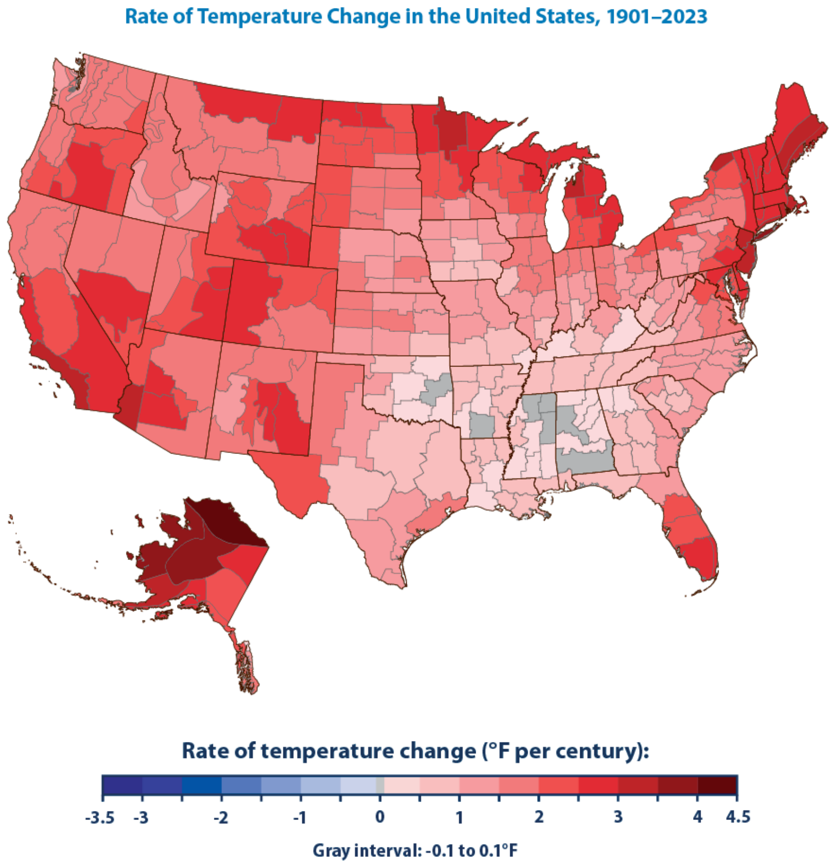


FIGURE 3.1 (Top) Temperature in the United States. (Bottom) Rate of temperature change.
SOURCE: EPA, 2025f.

in the last 50 years across all world regions, including the United States" (p. ES-3). Multiple independent datasets concur that the frequency and intensity of record heat—hot days, hot nights, heat waves—have risen while record cold—cold days, cold nights, and frost—have diminished over most land areas across the globe, including the United States (Fischer et al., 2025). These findings have been documented and reconfirmed in national and international climate assessments since 2009 (Eyring et al., 2021; USGCRP, 2023), as well as by records compiled by EPA's Climate Change Indicators (EPA, 2025f) for the United States.

EPA's Heat Waves Indicator (EPA, 2025c), based on six decades of observations, documents a tripling of average annual heat-wave frequency since the 1960s, with earlier starts and later ends to the season; regional studies reinforce these patterns. Weather events are classified as "extreme" relative to local historical baselines, so regional variability in these observations and events is expected. The frequency of extreme heat events is significantly increasing in the western United States, while seasonally relative extreme heat events are increasing in parts of the South (Ibebuchi et al., 2025). The Southeast experienced intensification of extremes—annual occurrence of the hottest day, the warmest night, warm days, warm nights, summer days, tropical nights, and warm spells—over 1978–2017 (Fall et al., 2021). Florida's observed heat-stress metrics (heat index, wet-bulb globe temperature) have risen markedly since 1950 (McAllister et al., 2022), while relative extreme cold events are decreasing the most in the Florida peninsula, as well as in southern California and Nevada (Ibebuchi et al., 2025). Analyses of cold air outbreaks and cold waves find broad declines in frequency, duration, and severity across the northern mid-latitudes, including in the United States (Smith and Sheridan, 2020; van Oldenborgh et al., 2019).

Extreme weather events most closely related to temperature have been found to be more frequent and intense due to human-caused climate change using extreme event attribution science (NASEM, 2016). Non-climate factors can also drive extreme temperature events and have done so in the past in the United States. The Dust Bowl is an example of a natural La Niña drought event and extreme temperature event that was exacerbated by human-caused land-use change and poor agricultural practices. These temperature extremes held records in the Great Plains that have only been surpassed in recent years (Meehl et al., 2022). Models using only sea-surface temperatures during the 1930s show that the natural drought would have occurred farther south without human-induced land-use change (Cook et al., 2009). More recent modeling studies show that the extreme drought of the Dust Bowl caused anomalous temperatures of +7.9°F (4.4°C) in the Great Plains and +0.56°F (0.31°C) over the North American landmass (Meehl et al., 2022). Meehl et al. (2022) shows that regional practices like extreme land-use misuse could have temperature extreme implications not only regionally but for the entire United States.

3.3 PRECIPITATION AND HYDROLOGICAL SYSTEMS

A warmer atmosphere increases the maximum amount of water vapor a volume of air can hold at a specific temperature, which can increase the potential for heavy precipitation even where annual total precipitation changes little (Eyring et al., 2021; USGCRP, 2023). Warming also increases evaporative demand (vapor pressure deficit) and shifts snow-to-rain ratios and snowmelt timing, changing soil moisture and streamflow seasonality. The balance of precipitation versus evapotranspiration[4] determines drought type and severity.

Atmospheric Moisture

Observations indicate a global increase in surface specific humidity[5] from 1973 to 2019 (Eyring et al., 2021; Gulev et al., 2021). This trend is also apparent for the United States (Marvel et al., 2023) and is consistent with the increased water holding capacity of a warmer atmosphere. Although the specific humidity is increasing, relative humidity is expected to remain approximately constant as the atmosphere warms. The increased specific humidity means the atmospheric water vapor content is also increasing systematically at a rate of approximately 7% for

[4] Evapotranspiration is the sum of all processes by which water moves from the land surface to the atmosphere via evaporation (e.g., into the atmosphere from the soil surface or bodies of water on land) and transpiration (water movement from the soil to the atmosphere via plants).

[5] Specific humidity measures the actual mass of water vapor in a unit mass of air. Relative humidity expresses how close the air is to saturation, as a percentage of the maximum water vapor it can hold at a given temperature; it therefore varies with temperature, since warmer air can hold more moisture than cooler air.

each degree Celsius of warming experienced. This increase is both well understood and well documented from global observations (e.g., Santer et al., 2007).

Water vapor accounts for half of the planet's greenhouse effect and amplifies the effect of GHG-induced warming. Increased water vapor has a number of important consequences for the hydrological cycle, in addition to amplifying GHG-induced warming. Storms are producing more intense rains in part due to this increased water vapor (see following sections) (Marvel et al., 2023).

Patterns of Precipitation

Over the oceans, multi-decadal salinity analyses show that the spatial patterns of precipitation have not appreciably changed (e.g., Durack, 2015; Durack and Wijffels, 2010). However, the amplitudes of the patterns of precipitation and evaporation over oceans have increased, consistent with the "wet-get-wetter, dry-get-drier" paradigm[6] of change. This is because as temperatures increase, the air holds more water vapor (up to 7% per degree Celsius of warming), a property known as the Clausius-Clapeyron relation. Therefore, warmer air increases evaporation over the ocean, holds more water, and increases heavy rainfall. The implication is that the global hydrological cycle is intensifying, at least over the global oceans.

Land-based hydrologic trends are complex and not as straightforward as those over the oceans. Between 1980 and 2015, water and climate data for the contiguous United States (from National Climate Assessment Land Data Assimilation System reanalysis), indicate coherent shifts in precipitation across the country (Jasinski et al., 2019). These shifts reinforce trends noted in previous studies, with mean precipitation increases of 0.12 to 0.35 inch (3 to 9 millimeters) per year in the upper Great Plains and Northeast and decreases from –0.04 to –0.35 inch (–1 to –9 millimeters) per year in the West and South. Patterns of change in terrestrial water storage, revealed by NASA's GRACE and GRACE-FO satellites, mirror these precipitation trends. The GRACE data have shown that the areas experiencing drying globally have increased by twice the size of California annually, creating "mega-drying" regions across the Northern Hemisphere. While most of the world's dry regions are becoming drier and wet regions wetter, the water storage data show that the rate of drying now exceeds the rate of wetting (Chandanpurkar et al., 2025). The observations of precipitation and water storage are consistent with the findings from EPA (2009a) that "changes are occurring in the amount, intensity, frequency and type of precipitation" (p. ES-2).

Extreme Precipitation

Long records of surface precipitation increasingly reveal a systematic shift in precipitation intensity. Fowler et al. (2021) offer an extensive review of surface rain gauge data analysis and present evidence from these observations supported with theoretical and modelling studies for the intensification of (1–3 hour) rainfall extremes. Both short-duration and long-duration (>1 day) rainfall extremes are intensifying with warming at a rate consistent with the increase in atmospheric moisture (~7% per degree Celsius), a finding supported by multiple decades of satellite observations. In some regions, short-duration extreme rainfall events exhibit much larger intensification than expected from moisture increases alone. These stronger local increases are related to feedbacks in convective clouds, though the strength and mechanisms of these cloud–radiation feedbacks remain uncertain (e.g., Stephens et al., 2018). Intensification of short-duration extremes confirmed in existing data records has likely increased the occurrence of flash flooding at local scales. EPA (2009a) projected the potential for increases in regional heavy downpours and occurrence of flooding that have now been confirmed by the observational record.

In the United States, the amount of land area experiencing greater than normal annual precipitation totals has increased since 1895, and the prevalence of extreme single-day precipitation events has risen substantially since the 1980s (Figure 3.2). These precipitation observations vary both year-to-year and across different regions of the United States (EPA, 2025d). Regionally, the Northeast has experienced about a 60% increase in the amount of

[6] The concept that dry regions dry out further, whereas wet regions become wetter as the climate warms has been proposed as a simplified summary of theoretically expected (e.g., Chou et al., 2009; Held and Soden, 2006) as well as observed changes over ocean (Durack et al., 2012), whereas land responses are more complicated (Greve et al., 2014).

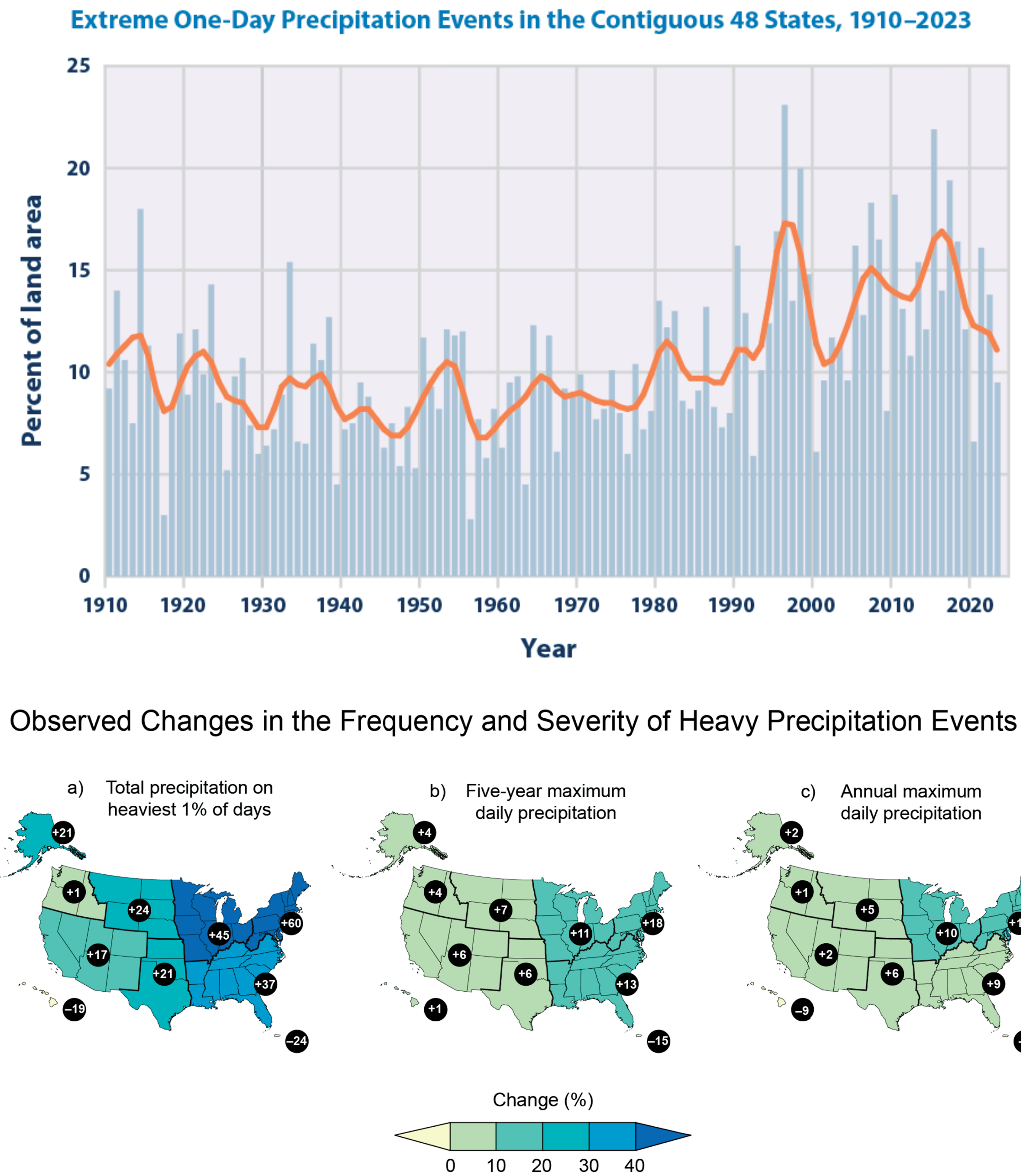


FIGURE 3.2 (Top) Extreme 1-day precipitation events in the contiguous United States, 1910–2023, and percentage of land area of the contiguous states where much greater than normal portion of total annual precipitation has come from single-day precipitation events, 1910–2023. The bars represent individual years, while the line is a 9-year weighted average. (Bottom) The frequency and intensity of heavy precipitation events have increased across much of the United States, particularly the eastern United States, with implications for flood risk and infrastructure planning. Maps show observed changes in three measures of extreme precipitation: (a) total precipitation falling on the heaviest 1% of days, (b) daily maximum precipitation in a 5-year period, and (c) the annual heaviest daily precipitation amount over 1958–2021. Numbers in black circles depict percent changes at the regional level. Data were not available for the U.S.-Affiliated Pacific Islands and the U.S. Virgin Islands.
SOURCE: (Top) EPA, 2025d. (Bottom) Marvel et al., 2023.

precipitation falling on the heaviest 1% of days since 1958 (Whitehead et al., 2023), with the Midwest up roughly 45% over similar periods (USGCRP, 2023). Along the West Coast, landfalling atmospheric rivers[7] have warmed in recent decades (Gonzales et al., 2019), favoring more rain over snow; multiple reanalysis-based studies detect strengthening characteristics of atmospheric rivers (Henny and Kim, 2025). Detection-and-attribution analyses using observed records also identify a human contribution to intensifying 1- and 5-day precipitation extremes (Sun et al., 2021).

Storms

Warmer water temperatures are expected to strengthen tropical cyclones globally (USGCRP, 2023). Although hurricane landfalls in the United States have not increased, hurricane activity in the North Atlantic has increased since the early 1970s (USGCRP, 2023). A trend has emerged of more rapid intensification of hurricanes since the early 1980s, as well as a slowdown in the rate of decay of hurricanes since the 1960s (Kossin et al., 2020; USGCRP, 2023).

Along the North American coast, observations have shown storms slowing down or stalling, bringing more heavy rainfall, wind damage, storm surge, and coastal flooding (Kossin, 2018; USGCRP, 2023). The destructive power of individual tropical cyclones through flooding is amplified by rising sea level, which very likely has a substantial contribution at the global scale from anthropogenic climate change (Knutson et al., 2021). The amount of tropical cyclone-related rainfall that any given local area will receive increases as the rain rates at the center of the cyclones increase.

Drought

Drought conditions have also varied over space and time in the United States. Meteorological droughts (i.e., periods of low precipitation) have increased in the southwestern United States and parts of the southeastern United States from 1915 to 2011. A mixture of positive and negative trends is observed elsewhere in the contiguous United States (Apurv and Cai, 2021). Analyses that incorporate evapotranspiration (i.e., evaporation from soils and open water plus plant transpiration) in addition to temperature to consider soil-moisture drought show a similar pattern with increasing trends in dry area coverage in the southwest and slight decreasing trends in the rest of the contiguous United States (Su et al., 2021).

Drought can also be characterized as a sustained imbalance between precipitation and evaporation. Rising temperatures associated with climate change have accelerated the hydrologic cycle by increasing evapotranspiration. While greater evapotranspiration places more moisture in the atmosphere and can enhance precipitation, it also promotes drying over land and reduces soil moisture in many areas. This pattern is consistent with observations in certain regions: an extended period of drought conditions in the southwestern United States has been observed from 2012 to 2023 (EPA, 2025j); drought in this region was also noted in EPA (2009a) from 1999 to 2008.

Since 2009, evidence of these changes has improved through expanded soil-moisture and snow remote sensing, improved reanalyses for drought process diagnostics, and clearer attribution of heat-driven aridity to anthropogenic warming in the western U.S. drought signal (USGCRP, 2023; Williams et al., 2022). Further, human-caused warming has changed the main driver of the soil moisture droughts over the western United States, from precipitation deficit to heat-driven high evaporative demand, since 2000 (Zhuang et al., 2024).

3.4 OCEAN HEAT AND CHEMISTRY

Ocean Heat Content

The evidence that the ocean has warmed as a result of excess GHGs has grown stronger since EPA (2009a). Because water has a much higher heat capacity than the atmosphere, the ocean is the main reservoir for heat in

[7] Atmospheric rivers are bands of condensed water vapor in the atmosphere that cause significant levels of precipitation.

the climate system. Ocean warming starts at the surface but is transferred to deeper layers by ocean circulation. An accurate estimate of ocean heat content is fundamental to understanding the evolving climate system and fundamental in the estimation of the Earth energy imbalance (Section 2.3). A robust increase in global sea surface temperature has been observed since 1900 (Garcia-Soto et al., 2021), and increases in summer upper-ocean stratification are apparent from 1970 to 2018 (Sallée et al., 2021). Increases in the heat content of the upper approximately 6,560 feet (2,000 meters) of the ocean are also evident since 1960 throughout the global oceans (Garcia-Soto et al., 2021), consistent with the Earth's energy imbalance (see Figure 3.3).

The advent of the Argo float network in 2004 greatly improved the spatial and temporal coverage of *in situ* measurements of temperatures in the upper layer of the ocean, which previously had been measured by electronic instruments lowered from ships. Currently, more than 3,900 Argo floats provide about 140,000 temperature (and salinity) profiles per year from the sea surface to about 6,560 feet (2,000 meters) depth at places across the globe (NASEM, 2017b). The Deep Argo program, which began in 2014 and expanded in 2016, advanced sampling of temperatures down to about 19,685 feet (6,000 meters) depth and enabled estimation of ocean heat gain over the full water column.

Heat absorbed by surface ocean waters is transported laterally and vertically through the layers and basins of the ocean via mixing and currents. Regionally, subsurface ocean temperature can also vary substantially with climate patterns such as El Niño, the Pacific Decadal Oscillation, the North Atlantic Oscillation, and large variations in wind stress over the ocean. On a regional basis, closure of the heat budget requires observations of ocean heat content, air-sea heat exchange, heat transport by ocean currents, and mixing.

Ocean warming has contributed to increases in rainfall intensity, rising sea levels due to thermal expansion, the destruction of coral reefs, declining ocean oxygen levels, and declines in ice sheets, glaciers, and ice caps in

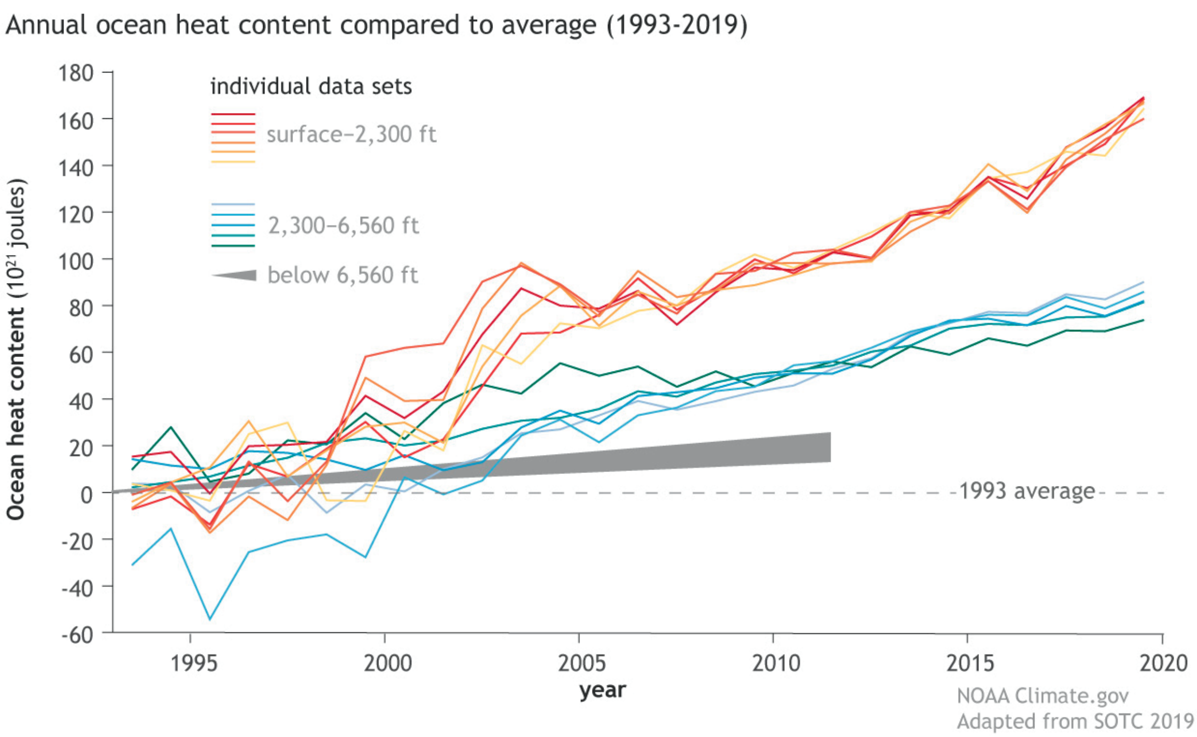


FIGURE 3.3 Annual ocean heat content compared to the 1993 average from 1993 to 2019, based on multiple data sets. Surface to depths of 2,300 feet (700 meters) in shades of red, orange, and yellow; from 2,300 to 6,650 feet (700–2,000 meters) in shades of green and blue; and below 6,650 feet (2,000 meters) as a gray wedge.
SOURCE: NOAA, 2025b.

the polar regions (Cheng et al., 2019; Hamlington et al., 2022). This warming is also one of many factors that has increased the number of low-oxygen dead zones in many places around the United States (USGCRP, 2023).

Marine Heat Waves

Marine heat waves are periods of anomalously high regional surface ocean temperatures. These events were not included in the evidence in EPA (2009a) but have become common in recent decades. These heat waves have considerable, detrimental impacts on marine ecosystems and the services that they provide (e.g., Frölicher and Laufkötter, 2018; Smale et al., 2019; Smith et al., 2024). In 2024, 91% of the global ocean was affected by at least one marine heat wave, while 26% experienced at least one cold spell (Blunden and Reagan, 2025). Laufkötter et al. (2020) show that the frequency of these events has increased more than 20-fold since preindustrial times, when it is estimated that they typically occurred with a frequency of once in hundreds to thousands of years. From 1982 to 2023, the annual cumulative intensity of marine heat waves increased across almost all waters in the U.S. exclusive economic zone, except for a nearshore region from Georgia to North Carolina (see Figure 3.4) (EPA, 2025e). The largest changes are present in Alaskan coasts and waters off the northeastern United States.

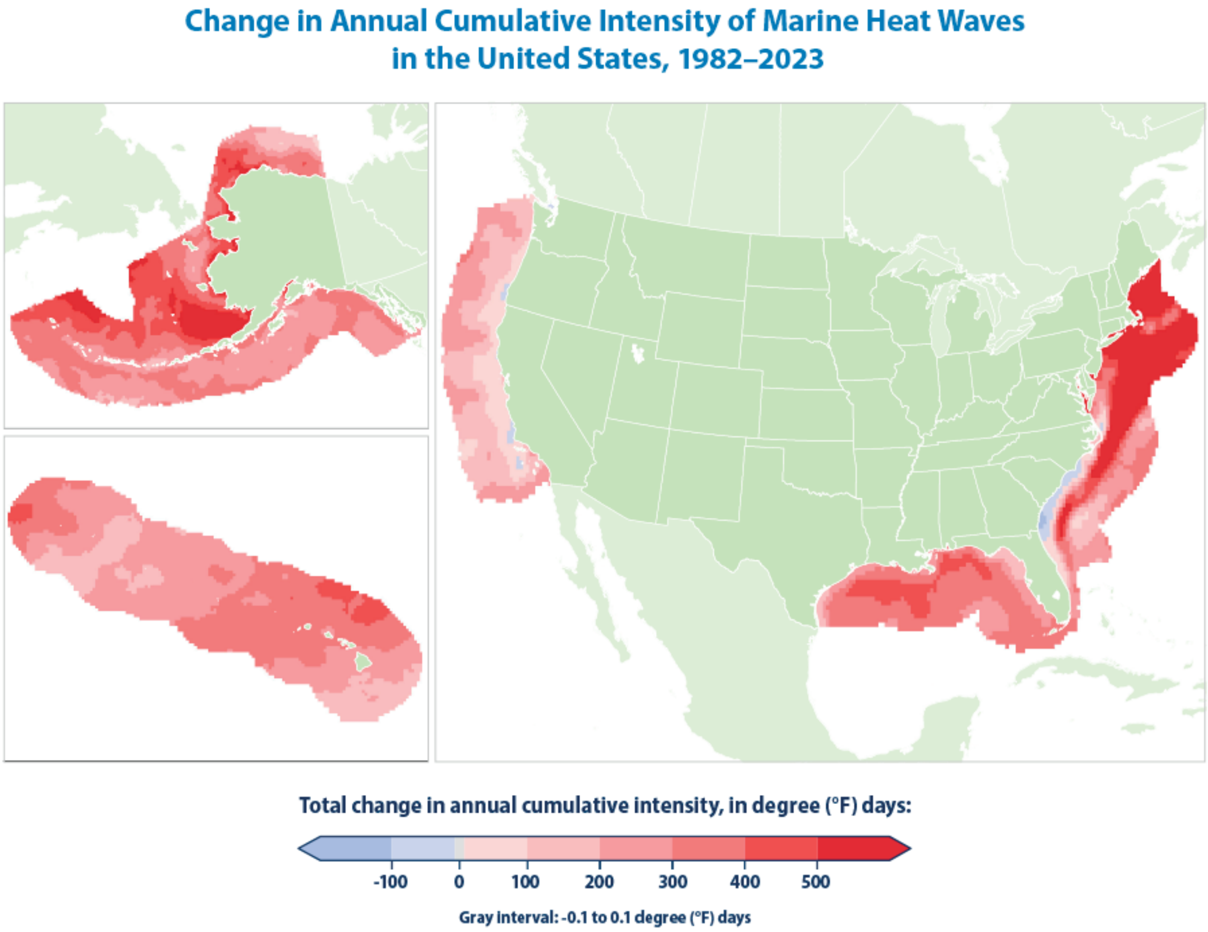


FIGURE 3.4 Change in annual cumulative intensity of marine heat waves in the United States, 1982–2023. Cumulative intensity is measured in degree days—marine heat wave intensity multiplied by duration. Areas with increases are shown in red, with darker colors indicating greater change. The map shows total change, which is the annual rate of change (trend slope) multiplied by the number of years analyzed.
SOURCE: EPA, 2025e, with data from NOAA NCEI.

Ocean Chemistry

Continued observations of ocean chemistry since 2009 affirm the conclusions in EPA (2009a) about uptake of excess CO_2 from the atmosphere. The ocean has taken up about 30% of the CO_2 emitted to the atmosphere over the past century (Gruber et al., 2019). Uptake of CO_2 in the ocean leads to a series of chemical reactions that lower the pH, increase concentrations of dissolved organic carbon, and increase the solubility of calcium carbonate. Calcium carbonate is an important component of the shells and skeletons of many marine organisms. EPA (2009a) noted that ocean pH had decreased from 8.2 in 1750 to 8.1 today, following a trend that has continued since 2009. Because the pH scale is logarithmic, a 0.1-unit decrease represents about a 30% increase in the hydrogen ion concentration in ocean water, which makes it less alkaline. The Intergovernmental Panel on Climate Change (IPCC) has assessed that it is virtually certain that human-caused CO_2 emissions are the main driver of the current global decline in pH of the open ocean's surface; a pH decline in the ocean interior over the past 2 to 3 decades has also been observed in all ocean basins (with high confidence) (IPCC, 2021). The decline in pH in U.S. offshore waters tracks with the global average trends, but changes in U.S. coastal waters vary due to upwelling conditions and nutrient and freshwater inputs that also lower the pH of ocean water (USGCRP, 2023).

Changes in ocean pH are monitored through *in situ* measurements of pH and partial pressure of CO_2 (a measure of the quantity of CO_2 dissolved in seawater). The number of moored and shipboard sensors for pH and CO_2 have increased greatly over the past decade and now provide more accurate monitoring information than in 2009. The rise in atmospheric CO_2 concentration concurrent with *in situ* measurements of pH and the partial pressure of CO_2 in ocean water clearly illustrate a cause-and-effect relationship between these variables over the long-term. Ma, Gregor, and Gruber (2023) used *in situ* and satellite observations to examine the trend in ocean pH from 1982 to 2021, confirming that the declining pH across the global ocean is attributable to the increase in the partial pressure of CO_2 from human-caused increases in atmospheric CO_2. The IPCC estimates in the *Special Report on the Ocean and Cryosphere in a Changing Climate* (IPCC, 2019) that the rate of ocean surface pH decline is 0.017–0.027 pH units per decade across a range of time series that are longer than 15 years. Bates and Johnson (2020) found that seawater CO_2-carbonate chemistry conditions today clearly exceed seasonal changes observed in the 1980s.

The study of ocean pH decline and its effects on marine organisms has expanded dramatically over the last two decades (Browman, 2016), and research demonstrates varied responses among various communities and species, with calcifying species (including corals) generally exhibiting more sensitivity to higher CO_2 (Doney et al., 2020; Kroecker et al., 2013). The extent to which the effects of ocean pH decline on marine biota will impact human welfare is an area of active research. Some areas of focus include potential impacts on economics of commercial fisheries and tourism, cultural values, and role in coastal protection for corals (Doney et al., 2020). See Chapter 6 for further discussion of impacts.

3.5 CHANGES IN PHYSICAL AND BIOLOGICAL SYSTEMS

EPA (2009a) documented a number of changes in physical and biological systems, including in the cryosphere, hydrosphere, and biosphere. The report highlighted the finding from IPCC (2007) that "anthropogenic warming has had a discernible influence on many physical and biological systems" (p. 53), but also noted that other factors, such as land-use change or natural decade-scale climate variations (such as the Pacific Decadal Oscillation) were likely to play a role.

Since EPA (2009a), data records have lengthened, data coverage has improved for some variables (e.g., mountain glaciers), new data sources have become available (e.g., ICE-Sat2 and GRACE satellites), and improved methodologies have been devised for assessing change. The changes in physical and biological systems documented in 2009 have generally continued and in some cases become more clearly attributable to a human influence (IPCC, 2019, 2021).

Cryosphere

The trend in annual mean Arctic sea ice extent remains similar to that documented in EPA (2009a), with a loss per decade of ~500,000 square-kilometers (about 4.5% relative to the 1981–2010 average) for the period of 1979–2023 (Fetterer et al., 2025). Sea ice has decreased in all months relative to the historical average, with the largest reductions in September equaling about 12.2% per decade for 1979–2023 relative to 1981–2010. The melt season has also lengthened from 1979 to 2023, with both earlier melt onset and later freeze-up (EPA, 2025b). A pause in September sea ice loss has occurred in the last two decades. This pattern is consistent with internal climate variability (England et al., 2025) and was anticipated in work showing that decadal pauses in ice loss are possible when anthropogenic ice loss is counteracted by internal variability (Kay et al., 2011).

EPA (2009a) noted that for the 1979–2008 period, Antarctic sea ice exhibited no significant change. However, since that time, Antarctic sea ice has undergone a significant loss. A small but significant increase in ice extent occurred from 1979 to 2014. This was followed by a dramatic ice loss in austral spring of 2016. Ice extent has remained remarkably low during the last decade with losses comparable to the 46-year record of Arctic sea ice decline (Abram et al., 2025). This has led to the suggestion that a regime shift may have occurred in the Antarctic sea ice system (Hobbs et al., 2024; Purich and Doddridge, 2023).

The other cryospheric changes documented in EPA (2009a) have generally continued. For the 1961–2016 period, glacier mass has been lost globally (Zemp et al., 2019), with glaciers in Alaska losing 3,000 gigatons (equivalent to 0.31 inches, or 8 millimeters, of sea level rise) and in western Canada and the western United States losing 428 gigatons (equivalent to about 0.04 inches, or 1 millimeter, of sea level rise) of mass. Permafrost continues to warm and thaw, and lake ice cover has declined (IPCC, 2019; Vonk et al., 2015). Northern Hemisphere spring snow cover has continued to decline, with a loss since 1922 of approximately 0.3 million square-kilometers per decade (IPCC, 2021).

Sea Level

As discussed in the previous sections, Earth's energy imbalance has led to warming of the surface, and 90% of the excess heat has been absorbed by the oceans. This has led to thermal expansion of the oceans which, together with land ice mass loss, contribute to sea level rise. Global mean sea level has risen about 7 inches (approximately 18 centimeters) since 1900, up from 6.7 inches reported in EPA (2009a).

Over the past three decades, satellites have provided continuous, accurate measurements of sea level on near global scales. EPA (2009a) reported the global average rate of sea level rise from 1993 to 2003 as measured by satellite altimetry to be about 0.12 inch (3.1 millimeters) per year; recent studies show the rate increased from about 0.08 inch (2.1 millimeters) per year in 1993 (the first year in previous averaged period) to about 0.18 inch (4.5 millimeters) per year in 2023 (Hamlington et al., 2024). This acceleration of the rate of sea level rise has been evident in both tide gauge and satellite altimetry records (Eyring et al., 2021; Sweet et al., 2022).

Regional relative sea level (see Figure 3.5) rose on average by approximately 11 inches (28 centimeters) in the last century along the continental United States, with about half of this amount (5–6 inches, about 13–15 centimeters) in the last 30 years (USGCRP, 2023). The greatest rise in regional relative sea level during that time (9 inches, about 23 centimeters) was along the U.S. western Gulf Coast, largely due to land subsidence from groundwater and fossil fuel extraction. Comparatively, regional relative sea level rise along the northeast and southeast Atlantic and eastern Gulf coasts was approximately 6 inches (about 15 centimeters). Along the Pacific Coast, natural modes of variability (the El Niño–Southern Oscillation and Pacific Decadal Oscillation) will continue to drive decadal variability in the rate of sea level rise.

Risks from rising sea levels include increased coastal flooding and increased vulnerability to coastal storms. Changes in average sea level have doubled the frequency of high tide flooding in the continental United States over the past few decades (USGCRP, 2023). In some cities, higher rates of local sea level rise have increased flood frequency. For example, using data from 1998 to 2013, Wdowinski et al. (2016) showed that significant changes in Miami Beach, Florida, flood frequency occurred after 2006, with four times as many disruptive high tide flooding events compared to the 1998–2005 period.

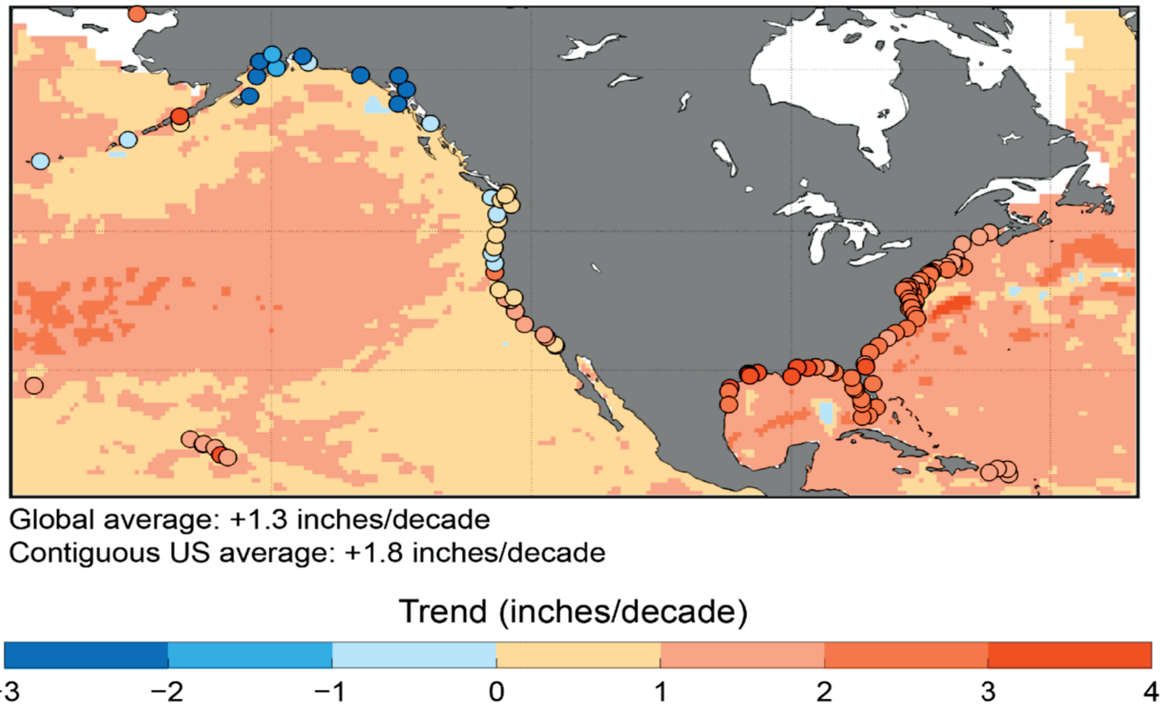


FIGURE 3.5 Observed sea level trends in the United States, 1993–2020. Data from tidal gauges and satellites show that on average the United States sea level rise trends are higher than the global average. The highest rates of sea level rise are shown in red and occur on the Atlantic Coast and Gulf region, while low rates of sea level rise are shown in blue and occur along parts of the Pacific and Alaskan coasts.
SOURCE: Marvel et al., 2023.

Longer observational records have increased confidence in estimates of human-caused sea level rise and acceleration in the rate of increase. Furthermore, with the benefit of a longer record, patterns and influences of natural variability of the ocean on interannual to decadal timescales can be more readily identified. This strengthens confidence since EPA (2009a) to support the conclusion that "global sea level gradually rose in the 20th century and is currently rising at an increased rate" (p. ES-3).

Biosphere

As discussed in previous sections, global increases in GHGs result in increases in global temperature, which in turn affects atmospheric and ocean circulation. These changes alter local weather conditions including increased local air or sea surface temperature (see Section 3.2) and precipitation and evapotranspiration patterns that control the moisture status of soils (see Section 3.3). Local conditions drive environmental forcings that can impact ocean chemistry (see Section 3.4) and sea level rise (see Section 3.6), as well as temperature and moisture stress; increased floods, drought, wildfire or wind events; and increased freshwater inputs to coastal areas.

These conditions control ecosystem response to climate changes, including increases in the frequency and severity of disturbance, incidence of novel disturbances, changes in primary productivity, changes in the movement of organic and inorganic matter, and altered populations and communities. Changes in these systems that most directly relate to impacts on human health and public welfare are discussed in more detail in Chapters 5 and 6—for example, how changing temperature and precipitation patterns can impact ecosystems, crops, livestock, and water resources (public welfare, Chapter 6), as well as impacts on the distribution of vector-borne diseases and allergens (human health, Chapter 5).

Ground-Level Ozone

As EPA (2009a) described, climate change affects ground-level ozone by modifying precursor emissions (other compounds that produce ozone through chemical reaction in the atmosphere), atmospheric chemistry, transport, and removal. USGCRP (2023) expanded on climate-sensitive factors driving increases and decreases in ozone concentrations, which include temperatures, heat waves, wildfires, drought, and biogenic emissions. Climate change can also reduce ozone pollution through increasing humidity. Climate change-induced changes in precipitation do not affect ozone, and effects of climate change-induced changes in regional transport and stagnation are unknown (USGCRP, 2023).

New studies further corroborate the effects of climate change on ground-level ozone reported in EPA (2009a) (USGCRP, 2016, 2023). Historical climate change has increased peak season ozone concentrations over North America (Turnock et al., 2025). Ozone increases driven by climate change may put some areas of the United States into nonattainment with the ozone National Ambient Air Quality Standard (Chang et al., 2025; East et al., 2024). Wildfires release ozone precursor gases and therefore can worsen ozone concentrations (Cooper et al., 2024), including far downwind of the fire; this is demonstrated by, for example, fires in Canada increasing ozone in the U.S. Midwest (Cooper et al., 2024) and fires in California, Washington, and Arizona increasing ozone in northern Colorado by 8 parts per billion in July 2021 (Langford et al., 2023). Studies find increasing co-occurrence of ground-level ozone with fine particulate matter, wildfire smoke, and heat extremes (Kalashnikov et al., 2022). Ozone, heat, and particulate matter can act synergistically on biological systems, leading to worse health outcomes compared with ozone exposure alone (see Chapter 5) (Anenberg et al., 2020; Fann et al., 2021; He et al., 2025; Remigio et al., 2021).

In addition to the impacts of climate change on ground-level ozone, CH_4 is both a potent GHG and a precursor for ground-level ozone. While local, daily variations in ozone concentrations are largely driven by reaction of non-CH_4 volatile organic compounds with nitrogen oxide emissions in the presence of sunlight, decades of research show that CH_4 also influences long-term average ozone concentrations globally and in the United States (Fiore et al., 2002; Fiore et al., 2008; McDuffie et al., 2023; Shindell et al., 2024; West and Fiore, 2005; West et al., 2006; Zhang et al., 2016). One study estimated that global CH_4 increases contributed 15% of observed trends in daily maximum 8-hour average ozone over the western United States from 1980 to 2014 (Lin et al., 2017).

3.6 WILDFIRES

The evidence supporting the EPA (2009a) discussion of impacts of climate on wildfires has strengthened greatly since 2009, as the occurrence of wildfires in the western United States has increased (Abatzoglou and Williams, 2016; Duffy et al., 2018). While records show a deficit in widespread fire relative to pre-1880 fire regimes, this is largely a result of fire suppression (Parks et al., 2025). Despite this deficit, wildfire intensity has been amplified by climate change (Jones, Veraverbeke et al., 2024; Parks and Abatzoglou, 2020), even under human fire suppression.

Increasing wildfire severity and annual area burned are linked to climate change (USGCRP, 2023). Warmer springs, prolonged summer dry periods, and progressively drier soils and fuel sources increase the likelihood for wildfire ignition and spread (Ostoja et al., 2023). Earlier snowmelt and diminished snowpack reduce water availability during peak summer heat, further lowering fuel moisture and enabling hotter, more intense burning. These dynamics are expected to persist as droughts become more frequent and longer in duration in some regions within the United States. Since 2009, these same drivers—earlier spring onset, longer summer dryness, and cumulative drought stress—have continued to lengthen the fire window and raise the probability of large, fast-spreading events, especially in the western United States.

Observations have been consistent with these mechanisms. In the West, both total burned area and the area burned at high severity have increased alongside warmer, drier fire seasons and higher vapor-pressure deficit (a measure of fuel aridity) (Abatzoglou and Williams, 2016). Synthesizing satellite burn-severity maps with incident records indicates roughly an eightfold rise in annual area burned and in high-severity burned area in western forests since the mid-1980s (EPA, 2025g). National indicators show greater acreage burned and longer fire seasons in the West relative to the East.

With increased wildfires, substantial amounts of particulate matter are produced (Law et al., 2025). Exposure to fine particulate matter is a known cause of mortality and cardiovascular disease and is linked to onset and worsening of respiratory conditions (see Section 5.3).

Wildfire Feedbacks

Changes in the water cycle are making forests in the western United States more susceptible to drought and wildfire. Moreover, increases in atmospheric nitrogen deposition and ground-level ozone shift the processing of water, carbon, and nitrogen in forest ecosystems, resulting in a cascade of synergetic effects that make trees more prone to disease, pest invasion, drought, and ultimately, wildfire. These air pollutants increase leaf turnover and litter mass and decrease the decomposition of litter (Gilliam et al., 2019). As a result, mixed conifer forests of southern California that are impacted by nitrogen and ozone pollution develop deep litter layers. Elevated ozone decreases plant control of water loss, increasing transpiration, which when coupled with loss of root mass, increases the susceptibility of trees to drought stress and makes them more vulnerable to attack by bark beetles, leading to significantly higher tree mortality (Jones et al., 2004).

The enhanced fuel load from tree decline and litter accumulation, coupled with historical fire suppression, increases in housing developments at the wildland–urban interface, and climate change, have resulted in catastrophic fires in northern and southern California in recent years, exacerbating air quality and health impacts. Such feedbacks are expected to continue to influence wildfires in the future, which would accelerate a deterioration in air quality and its associated impacts.

Wildfires also release large amounts of CO_2, CH_4, and other GHGs, as well as black carbon particles into the atmosphere, which contribute to climate warming, leading to a positive feedback loop that could further increase wildfire risk (NASEM, 2024e). Black carbon, a potent short-lived climate forcer present in wildfire smoke, accelerates glacier and snow melt and amplifies atmospheric warming. Elevated emissions from recent wildfires have been measured at levels equivalent to the annual fossil fuel output of major industrialized nations (Byrne et al., 2024). Jones, Veraverbeke et al. (2024) found that global CO_2 emissions from forest fires have surged by 60% since 2001 largely due to increasingly intense and wide-ranging wildfires.

3.7 WHIPLASH AND COMPOUND EVENTS

Back-to-back occurrences of severe floods and droughts (referred to as weather or hydroclimate whiplash[8]) have increased in frequency and severity around the world (Li and Rodell, 2023; Swain et al., 2025). Using a metric of "hydroclimate whiplash" based on the Standardized Precipitation Evapotranspiration Index, Swain et al. (2025) find that the global-averaged sub-seasonal (3-month) and interannual (12-month) whiplash events have increased by 31–66% and 8–31% respectively since the mid-twentieth century. Extensive evidence links those increases primarily to thermodynamics, namely the rising water vapor-holding capacity and potential evaporative demand of the atmosphere. These increases highlight how the response of the climate system to warming can be nonlinear in a way that compounds its impact on the environment.

Another form of weather whiplash occurs with winter weather events. Rapid swings in winter weather can result in crossing from frozen to unfrozen conditions, or vice versa; thus, the potential impact of these types of events on coupled human and natural systems may be large (e.g., Casson et al., 2019; Creed et al., 2023). It is less clear how climate change is altering these events given limited observational records and the infrequency of these events.

[8] In this context, "whiplash" refers to rapid swings from one extreme or specified climate state to another (e.g., from drought to flood or from frozen to unfrozen winter weather conditions).

Compound events involve multiple climate drivers or hazards that either occur together or in a connected sequence, either in an individual location or across multiple locations (e.g., Zscheischler et al., 2018). The combinations of climate drivers and hazards can result in significantly greater impact than occurs because of a single climate driver. For example, the 2017 wildfires in California were followed by intense rainfall events on burned landscapes, resulting in mudslides and debris flows (USGCRP, 2023). Another example is the September 2024 flooding in Asheville, North Carolina, after Hurricane Helene. When the hurricane was still more than 620 miles (1,000 kilometers) to the southwest of Ashville, western North Carolina experienced an extreme rainfall event, receiving 5–8 inches (125–200 millimeters) of rain in less than 24 hours. This predecessor extreme rainfall event occurred when the moisture associated with Hurricane Helene met a southeastward-moving cold front originating from the Northern Plains (Schreck, 2025). This rainfall event, combined with the rainfall associated with the hurricane directly, contributed to the flooding experienced in the region. USGCRP (2023) indicates that observed compound events across the United States are becoming more frequent and severe due in part to climate change, which intensifies the underlying physical drivers.

4

Impacts of Greenhouse Gas Emissions on Future Climate

4.1 KEY MESSAGES

EPA (2009a) provided projections of future changes in the climate system associated with human-caused greenhouse gas (GHG) emissions. Many of these projected changes have been observed since 2009, as described in Chapter 3, including increasing surface temperatures, higher sea levels, and regional variability across the United States in other physical and biological systems.

Continued emissions of greenhouse gases from human activities will lead to more climate changes in the United States, with the severity of expected change increasing with every ton of greenhouse gases emitted. Despite successful efforts in many parts of the world to reduce emissions, total global GHG emissions have continued to increase, and additional warming is certain.

Models have proven skillful and are effective at simulating a fingerprint of human influence on the changing climate that is now observed. Climate models, which simulate the Earth system, have been used since the 1960s to examine the role of different climate forcings in driving climate variability. Models have simulated certain "fingerprints" of the climate response to human-caused GHG emissions that have since been observed, including the vertical structure of temperature changes and enhanced warming over land relative to oceans.

All climate models—regardless of assumptions about future emissions scenarios or estimates of climate sensitivity—consistently project continued warming in response to future atmospheric greenhouse gas increases. Projections of future change draw primarily on physically based climate models, which have advanced in spatial resolution, process representation, and evaluation since 2009, improving confidence in understanding of the implications of future emissions. Applying fundamental physics of the Earth system leads to the same conclusion about future warming as projected by climate models.

Continued changes in the climate increase the likelihood of passing thresholds in Earth systems that could trigger tipping points or other high impact climate surprises. These surprises are difficult to predict, can occur abruptly, and, in some cases, would be irreversible.

4.2 CLIMATE MODELS

Climate models are numerical simulations of the Earth system, including the atmosphere, ocean, land, freshwater systems, and sea ice, and the coupling among these components. These models are based on the underlying physics that govern these systems and evolved from numerical weather prediction models, first developed in the

1960s (e.g., Manabe and Wetherald, 1967). Aided by improvements in their process[1] representation and improvements in supercomputers, these models have increased in complexity. These models are now often referred to as "Earth System Models" and can incorporate many additional components and processes, including terrestrial and marine ecosystems, atmospheric chemistry, land ice, and glacial dynamics.

Since the 1960s, climate models have been used to examine climate variations and the role of different climate forcers, such as GHGs and volcanic emissions, in driving that variability. They provide projections of future climate conditions subject to scenarios of future emissions of GHGs and aerosols, as well as land cover changes. They are also an important tool for attribution in that they allow for controlled experiments, for example by isolating the climate response to increasing GHGs versus other climate drivers (e.g., Gillett et al., 2016). Notably, these models have improved at simulating changes in the climate that have already been observed.

However, the climate system is complex, and models are imperfect tools. Climate projections have uncertainty due to internal variability in the climate system, uncertainty in future emissions of GHGs and aerosols, and structural uncertainty in the models themselves. Comparisons across models, which include different details of process representation and numerical implementation, are useful for quantifying structural model uncertainty (e.g., Hawkins and Sutton, 2009). A common metric used for this comparison is the equilibrium climate sensitivity (for a recent review, see Jeevanjee et al., 2025), which is the equilibrated global mean surface warming for a doubling of CO_2. A subset of climate models has equilibrium climate sensitivity that is higher than the likely range as assessed by the Intergovernmental Panel on Climate Change (e.g., Zelinka et al., 2020). Understanding why these models have a higher equilibrium climate sensitivity is an area of active research. That said, while this metric is useful for understanding climate response and model uncertainty, it has somewhat limited relevance for projected change in the near term because the climate system is not equilibrated and factors such as changing aerosol emissions play a role (Jeevanjee et al., 2025).

Since EPA (2009a), updates to climate models have occurred with the newest models available under the Coupled Model Intercomparison Project 6 (Eyring et al., 2016). As a group, these models have improvements to process representation and include additional capabilities. For example, advances have been made since 2009 in the ability for model ensembles to quantify the influence of internal climate variability on projections (Kay et al., 2015) and in model resolution. These improvements have enabled the use of models for new applications, such as multiyear prediction of flood frequency (Zhang et al., 2025) and extending the time horizon of tropical cyclones forecast to seasons (Murakami et al., 2025).

The availability of longer observational time series since EPA (2009a) has also allowed for improved validation of model-simulated trends in the historical record and improved understanding of model successes and challenges that are still present (Simpson et al., 2025). The models have allowed the detection of a "fingerprint" of human influence (see Section 2.4) across many observed changes in the Earth system (Eyring et al., 2021), including the vertical (Santer et al., 1996) and regional (Hegerl et al., 1996) structure of temperature changes, seasonal cycle changes for tropospheric (Santer et al., 2022) and sea surface (Shi et al., 2024) temperatures, and daily precipitation variability (Ham et al., 2023), among others.

While models are not perfect, they are useful and skillful tools for attribution of anthropogenic signals in the changing climate and understanding of future climate changes in response to GHG emissions. All climate models consistently project continued warming in response to future GHG increases, regardless of climate sensitivity levels or future emission scenarios. Notably, they are just one line of evidence of human influence on historical climate change. When combined with observational evidence, paleoclimate information, and theoretical understanding, it is unequivocal that many climate changes underway can be attributed in large part to rising GHG emissions from human activity. This evidence also indicates that every additional quantity of emissions will strengthen, and in some cases accelerate, those changes for the future.

[1] In climate and Earth system models, a "process" refers to a physical, chemical, or biological phenomenon—such as cloud formation, ocean circulation, or carbon uptake by plants—that influences the climate system and is described mathematically in the model.

4.3 EXPECTED CHANGES IN U.S. CLIMATE

The long lifetime of energy, transportation, industrial, and other built infrastructure creates challenges in rapidly reducing CO_2 emissions (NASEM, 2021b, 2024a). Hence, despite mitigation efforts in many parts of the world and the achievement of downward CO_2 emission trends in many advanced economies, total global emissions have continued to grow and are expected to remain near current levels over the coming decade.

Given the persistence of CO_2 and other long-lived GHGs in the atmosphere, past emissions have increased atmospheric concentrations of these gases, which will sustain Earth's energy imbalance (see Section 2.3). Warming will continue until net CO_2 plus N_2O emissions reach (and remain at) ~0 and emissions of CH_4 are constant or decreasing. As long as global emissions of CO_2 stay above zero, concentrations and radiative forcing will continue to increase and global temperature will increase roughly in proportion to cumulative CO_2 (i.e., each additional ton emitted adds an increment more to temperature increase) with small contributions from other long-lived gases including N_2O and F-gases. As global emissions of GHGs are spread across all nations, a collective effort at reducing emissions is required to limit future warming.

Analysis of policies in place in 2023 showed that CO_2e emissions would stay roughly constant over 2025–2035 (UNEP, 2024), driving continued warming that would lead to a projected peak global mean warming in 2100 of about 4.9°F (2.7°C) (4.1 to 5.4°F, or 2.3 to 3°C range) (Hausfather, 2025). Were all countries to fully implement their 2023 policies and their unconditional pledges to the United Nations Framework Convention on Climate Change, global CO_2e emissions would drop by ~5%, leading to a projected peak 21st-century warming of about 4.4°F (2.4°C), or only about 0.5°F (0.3°C) less than under current policies (UNEP, 2024). The likelihood of exceeding global mean 3.6°F (2°C) warming relative to preindustrial temperatures under these two cases is estimated at 97% with current policies continuing and 94% for unconditional pledges continuing (UNEP, 2024). Warming beyond 3.6°F (2°C) is expected to have many negative consequences for human health and welfare in the United States (see Chapters 5 and 6).

Emission scenarios used in simulations of projected climate (O'Neill et al., 2016; Riahi et al., 2017) have been updated since EPA (2009a). These scenarios encompass a range of possible futures, including high emissions scenarios, which assume significant "regional rivalry," and "sustainability" scenarios, which assume deep and sustained reductions in emissions, with net negative CO_2 emissions by 2100. Using this range of scenarios and large numbers of model simulations, projected impacts of future warming on the United States can be assessed probabilistically. Risks of future impacts for some quantities—including heat, sea level rise, and some extreme events—can be assessed with relatively high confidence, while risks for other expected impacts, including regional droughts and hurricane intensities, continue to have large uncertainties in their quantification. Climate-related damages increase with every quantity of GHGs emitted and the damages per ton of emissions also rise as the Earth continues to warm owing to non-linearities in impacts (Cissé et al., 2022; EPA, 2023). In simulations with sustained GHG emission reductions, the increase in atmospheric CO_2 concentrations slows after 5–10 years, and global warming slows after several decades (Lee et al., 2021). This is consistent with studies that examine the climate response to a complete cessation of CO_2 emissions, which indicate that temperatures would stabilize or even decrease over time (Jones et al., 2019; Matthews and Weaver, 2010).

With each increment of continued GHG emissions and warming, surface and near-surface air temperatures (and thus heat exposure to humans and, for example, crops, animals, and ecosystems) increase; extreme heat becomes more frequent and extreme precipitation events increase across some regions, while aridification and drought persist in others—patterns that often scale approximately linearly with global temperature, though not uniformly across all metrics or places (USGCRP, 2023). The oceans continue taking up heat and CO_2, driving higher ocean heat content, rising sea levels from thermal expansion and land-ice loss, and decline in ocean pH; these changes persist for decades to centuries even if temperatures stabilize (Lee et al., 2021). These findings are independent of the equilibrium climate sensitivity level in any specific model.

4.4 ABRUPT CLIMATE CHANGE

In response to increasing GHGs, many climate changes have been observed and are anticipated for the future. In many cases, these changes exhibit a roughly linear relationship to changed forcing, as with global temperature, discussed above. However, the climate system can also exhibit an abrupt response to climate warming when certain thresholds (sometimes referred to as "tipping points") are passed. Paleoclimate data indicate that abrupt shifts have occurred in the past (e.g., Capron et al., 2021). With continued and accelerating climate warming, the likelihood for surpassing thresholds grows with the potential for rapid and dramatic disruption to human systems (NRC, 2013).

EPA (2009a) states, "Climate warming may increase the possibility of large, abrupt regional or global climatic events" (p. ES-4). This was and remains accurate, supported by more evidence on additional possible "tipping elements" that could undergo abrupt change. EPA (2009a) discussed several specific elements where abrupt changes were possible, including megadroughts, disintegration of the Greenland Ice Sheet, collapse of the West Antarctic Ice Sheet, catastrophic release of CH_4 from sea floor CH_4-hydrates and/or permafrost soils, and slowing down of the Atlantic Meridional Overturning Circulation (AMOC)—which is a major component of Atlantic Ocean circulation. For many of these elements, abrupt change in the 21st century was considered to be low probability but high impact. There remains uncertainty in whether or when tipping points might be reached in these elements. For example, studies on AMOC simulate a range of responses to changing buoyancy (heat and freshwater) forcing (e.g., Jackson et al., 2023) and observation-based early warning systems may suggest a higher likelihood of collapse than seen within climate models (e.g., Ditlevsen and Ditlevsen, 2023). Paleoclimate evidence strongly suggests instances of AMOC collapse during the Younger Dryas, Heinrich events, and potentially during Dansgaard–Oeschger[2] events in the Last Glacial Period (e.g., Lynch-Stieglitz, 2017).

Since 2009, evidence has emerged for some abrupt changes underway. For example, numerous rapid changes in the Antarctic environment have occurred (Abram et al., 2025), including rapid reductions in sea ice (Purich and Doddridge, 2023), regime shifts in biological systems (e.g., Fretwell et al., 2023), and increasing ice sheet mass loss (Rignot et al., 2019), with consequences for sea level rise. Research has also highlighted additional potential "tipping elements," including rapid changes in numerous terrestrial and marine ecosystems, expansion of oxygen minimum zones, the potential collapse of the Antarctic Overturning circulation (Abram et al., 2025), and loss of alpine glaciers, among others (e.g., NRC, 2013). Assessments have quantified an increasing likelihood of passing multiple climate tipping points with increasing warming (e.g., Armstrong McKay et al., 2022), many of which could be irreversible. Work has also highlighted that tipping elements can interact and often do so in destabilizing ways, thus setting up the possibility of "tipping cascades" (Wunderling et al., 2024).

[2] Dansgaard–Oeschger (D-O) events are periods of rapid warming (over a few decades) followed by a slow cooling (over a few hundred years). During the Last Glacial Period, there were 25 recorded D-O events that occurred every few thousand years.

5

Impacts on Human Health

5.1 KEY MESSAGES

Human-caused emissions of greenhouse gases and resulting climate change harm the health of people in the United States. Evidence since 2009 supports and strengthens EPA (2009a) conclusions and has deepened the understanding of how these risks affect health. Climate-related illnesses and deaths are increasing in both severity and geographic range across the United States.

Climate change intensifies risks to human health from exposures to extreme heat, ground-level ozone, wildfire smoke and other airborne particulate matter, extreme weather events, and airborne allergens, affecting incidence of cardiovascular, respiratory, and other diseases. Much evidence is now available on how heat affects morbidity and mortality, not only by directly causing heat exhaustion and heat stroke, but also by worsening effects on cardiovascular, respiratory, kidney, mental health, and other disorders. New evidence has deepened understanding of how climate-sensitive drivers increase ozone pollution, how long-term ozone exposure leads to health effects beyond those of short-term exposure, and how health outcomes are amplified by co-occurrence of ozone exposure with heat and particulate matter exposure.

Climate change has increased exposure to wildfire smoke and dust, which has been linked to adverse health effects. Since 2009, wildfire smoke exposure has increased, particularly in the U.S. West, and new evidence has linked wildfire smoke exposure to a wide range of adverse human health outcomes, including respiratory disease and premature death. New evidence has also shown that climate change has increased airborne soil dust and associated health effects, particularly for areas that are warmer and drier, such as the U.S. Southwest.

The increasing severity of some extreme weather events, such as wildfires and heavy precipitation events, has contributed to injury, illness, and death in affected communities. Although non-climate factors, including adaptation, can mitigate the negative effects of climate change on health, extreme events can overwhelm the ability to respond. Extreme events can impact human systems, including health care and food systems, power systems, and other critical infrastructure, adding to the risks faced by individuals and communities.

Health impacts related to climate-sensitive infectious diseases—such as those carried by insects and in contaminated water—have increased. An increase in the geographic distribution of tick-borne diseases, anticipated in the 2009 report, has been confirmed and attributed to climate warming. Dengue, a mosquito-borne viral disease, has increased in activity and geographic range since the 2009 report, now appearing in people who have not traveled ("non-travelers") in Texas, Florida, Arizona, and Hawaii. Climate change is expanding the area of endemicity of some fungal diseases. Heavy precipitation, drought, and warming temperatures are linked to a rise in waterborne disease outbreaks.

New evidence is developing about additional health impacts of climate change. Newer areas of evidence include potential impacts on mental health, nutrition, immune health, antimicrobial resistance, kidney disease, and negative pregnancy-related outcomes. In addition, research has grown showing that combined exposure to multiple climate-sensitive risk factors, either simultaneously or cumulatively over time, worsens health outcomes.

Groups such as older adults, people with preexisting health conditions or multiple chronic diseases, and outdoor workers are disproportionately susceptible to climate-associated health effects. New findings also point to elevated risks for pregnant people and children. Even as non-climate factors, including adaptation measures, can help people cope with harmful impacts of climate change, they cannot remove the risk of harm.

Weather and climate interact with many factors to shape the effects of climate-sensitive health outcomes in any given place and time (Ebi et al., 2020). The climate changes discussed in preceding chapters affect human health directly through events such as heat waves or wildfires, as well as indirectly, through pathways like air and water quality and nutrition, with these impacts further shaped by broader environmental, social, and public health conditions (WHO, 2018). The climate and health field has expanded considerably since EPA (2009a) was published, with substantial new data and research strengthening the evidence base, deepening understanding of how climate change affects health, and clarifying the pathways through which these impacts occur. This chapter explores health effects from exposure to extreme temperatures and events such as wildfires and hurricanes, the influence of climate on infectious and noncommunicable diseases, and health implications of changes to air quality. Examples illustrate areas where knowledge has grown or evolved, including areas of health research not discussed in EPA (2009a).

EPA (2009a) concluded that negative health effects from climate change are experienced disproportionately by some populations. Subsequent assessments of the impacts of human-caused greenhouse gas (GHG) emissions and resulting climate changes have also concluded that these changes are harming physical and mental health (see discussion of GHG emissions and climate effects in Chapters 2 and 3) (IPCC, 2022a; USGCRP, 2023). The evolution of understanding the health risks from climate change since 2009 is summarized in Table 5.1. Evidence has continued to accumulate about multiple health effects; none of the areas identified in EPA (2009a) showed weakened evidence of health effects. Although this report does not consider the impacts of adaptation or mitigation measures in reducing climate-associated health risks in detail, Box 5.1 highlights a few potential ways such adaptations may influence risk as well as some of the potential limitations of such measures.

5.2 TEMPERATURE EFFECTS

EPA (2009a) concluded that "[s]evere heat waves are projected to intensify in magnitude and duration over the portions of the United States where these events already occur, with potential increases in mortality and morbidity, especially among the elderly, young, and frail" (p. ES-4). Observations continue to show a warming trend in regions of the United States, particularly in Alaska, the West, and the Northeast, with hot extremes increasing with cold extremes decreasing (see Section 3.2). Studies and assessments of human health consequences continue to support the EPA (2009a) conclusion that changes in average temperatures and increased exposure to temperature extremes contribute to adverse health outcomes in many places in the United States.

Studies on ambient temperature and health have identified U-, V- or J-shaped patterns in which extremes of both hot and cold are associated with adverse effects, recognizing that duration, humidity level, extent of divergence from a location's usual temperature, and other parameters influence these outcomes and that some groups are more susceptible to the effects of temperature than others (Burkart et al., 2021; Ye et al., 2012). For example, a 2023 study spanning 2000–2016 and involving 61.6 million Medicare beneficiaries aged 65 and older found that cardiovascular hospitalizations were higher in areas with hotter summers or colder winters (Klompmaker et al., 2023). USGCRP (2016) identified as a key finding that "[d]ays that are hotter than usual in the summer or colder than usual in the winter are both associated with increased illness and death [Very High Confidence]. Mortality effects are observed even for small differences from seasonal average temperatures [High Confidence]" (p. 6)

Health Effects Associated with Heat Exposure

Recent evaluations and assessments have highlighted the wide-ranging health consequences of exposure to increased temperature and heat (IPCC, 2022a; Lancet Countdown, 2024; USGCRP, 2023). Heat contributes to excess illness and death in the United States and globally, with an estimate of net increases in all-cause mortality risk associated with increased average annual temperatures from 0.1% to 1.1% per 1.8°F (1°C) (Cromar et al., 2022). According to data from the National Weather Service, heat is associated with more weather-related deaths than any other extreme weather event.[1]

Much evidence is now available on how heat affects morbidity and mortality, not only by directly causing heat exhaustion and heat stroke, but also by worsening effects on cardiovascular, respiratory, kidney, mental health, and other disorders (see Section 5.5 discussing climate-sensitive diseases). Heat waves are linked with higher rates of emergency department visits, hospitalizations, or deaths for such conditions (Khatana et al., 2022; Sun et al., 2021). Exposure to higher temperatures and heat stress are also linked to adverse pregnancy and birth outcomes (Baharav et al., 2023; Jiao et al., 2023; Khalili et al., 2025; Kuehn and McCormick, 2017; USGCRP, 2023; Weeda et al., 2024; Zhang et al., 2023).

Rising temperatures increase risks for workers in sectors such as construction, agriculture, transportation, warehousing, and waste management (USGCRP, 2023). Other outdoor workers, including those in landscaping, natural resources management, and firefighting, are also affected by outdoor temperatures, as are people who live in poorly insulated or unshaded homes and the unhoused. For example, a 2022 meta-analysis of occupational heat exposure examined 2,409 outdoor workers across 41 jobs in 21 countries, including the United States. The study's findings suggest that occupational heat stress elevated workers' core and skin temperatures, heart rate, and the concentration of dissolved chemicals and particles in urine (Ioannou et al., 2022). Among workers routinely exposed to heat stress (≥6 hours/day, 5 days/week, for ≥2 months annually), a study found that approximately 15% developed kidney disease or acute kidney injury (Flouris et al., 2018). Increased specific humidity in some heat-prone areas decreased evaporative cooling through sweat and was found to exacerbate heat stress, although results of epidemiological studies exploring the role of specific humidity in heat-related health outcomes have been mixed (Baldwin et al., 2023). With global warming, heat reaches unsafe thresholds for sustained labor earlier in the morning, making it harder to adapt shifts to safer hours (Parsons et al., 2021). Heat waves can also reduce the places where fans, rather than air conditioning, are able to provide sufficient cooling, amplifying the impacts on poorer communities (Parsons et al., 2023).

In the United States, recent studies have assessed excess heat-related deaths attributable to climate change, identifying impacts on mortality although finding that percentages attributable specifically to human-induced climate change remain relatively small. As noted for many health effects, a complex interplay of factors beyond a location's recorded temperature affects health outcomes. For example, one study that generalized local epidemiological evidence across the contiguous United States found 12,000 (95% confidence interval [CI] [7,400, 16,500]) heat-related premature deaths annually in the United States averaged over 2010–2019 (Shindell et al., 2020). Using data from sites in the United States and around the globe, researchers estimated that 37.0% (20.5–76.3%) of warm-season heat-related deaths could be attributed to human-induced climate change (34.7% in the United States); this analysis assessed that a 0.30% increase (95% CI [0.01, 0.76]) of heat-related mortality in the United States is attributable to human-induced climate change (Vicedo-Cabrera et al., 2021). A recent analysis of U.S. mortality during 1999–2023 in which heat was an underlying or contributing factor observed an increasing trend; further research will be needed to understand whether such a trend is directly attributable to climate change (Howard, Androne et al., 2024).

[1] See Weather Related Fatality and Injury Statistics at https://www.weather.gov/hazstat (accessed September 8, 2025).

TABLE 5.1 Assessment of Change in Evidence of Risks from Climate Change Since EPA (2009a)

Type of Effect	**Areas Addressed in EPA (2009a)**	**New Areas of Evidence Since EPA (2009a)**
Exposure to extreme heat	⬆	
Exposure to ground-level ozone	⬆	
Exposure to airborne particulate matter	⬆	
Exposure to extreme weather events	⬆	
Exposure to vector-borne diseases	⬆	
Development or exacerbation of chronic diseases	⬆	
Exposure to airborne allergens	⬆	
Effects on mental health		⬆
Effects on pregnancy and birth outcomes		⬆
Effects on nutrition		↑
Effects on immune health		↑
Effects on antimicrobial resistance		↑
Effects on metabolic diseases		↑

NOTES: Large arrows indicate topics for which the evidence has continued to accumulate. Small arrows indicate areas for which a potential health effect has been identified and further studies are ongoing.

Health Effects Associated with Exposure to Cold and Differential Impacts of Heat Versus Cold on Mortality

EPA (2009a) found that "Some reduction in the risk of death related to extreme cold is expected" as a result of climate change, but "it is not clear whether reduced mortality from cold will be greater or less than increased heat-related mortality in the United States" (p. ES-4). Many factors are involved in evaluating cold-induced deaths, and cold-related mortality reductions with climate change have not been observed and remain unclear.

Factors important to assessments of temperature-related morbidity and mortality include not only the temperature maximum or minimum itself, but also whether the extreme event happens earlier or later in the season, its duration, how it relates to temperatures normally experienced in that region, the influence of seasonality on infectious disease transmission, intersections with a person's age and the aging population, preexisting health conditions, and other physical and biological factors, including where they live and work (Healy et al., 2023; Liu et al., 2025). Some parts of the United States may experience increases in heat-related mortality and other locations

BOX 5.1
The Role of Adaptation in Reducing Risks to Human Health

Adaptation can help to reduce health risks from climate change. For example, heating and air conditioning can reduce risks from outdoor temperature extremes. A study of non-accidental death due to hot days found that this risk declined from 10.6% to 0.9% from the 1960s, associated with increases in air conditioning and controlling for parameters such as geographic location and mean summer temperature, while noting that "the remaining 20% of un-air-conditioned housing are not randomly located, but primarily in areas that have less summer heat, but where summer temperatures are likely to increase" (Nordio et al., 2015, p. 85).

The potential effectiveness of adaptation measures in reducing future climate-driven health risks is uncertain. Predicting their success requires assumptions about many factors that are unrelated to climate, including human behavior, government policies, and technological advances, which are not explored in detail in this report. Furthermore, there are limits to the ability to adapt to climate-associated health risks, benefits from available adaptations may be uneven and incomplete, and available adaptation approaches may differ in utility locally and regionally. In some instances, effective adaptation approaches are known but remain unimplemented or have been applied inconsistently. For other climate-related health risks, evidence-based adaptation strategies have yet to be identified.

Not all groups and communities have the same access to adaptations that mitigate health risks. For example, communication gaps can limit awareness of increased heat risks and readiness strategies to reduce such risks in places that have not historically dealt with high temperatures (Healy et al., 2023; Howe et al., 2019). Countries such as the United States show weaker temperature–mortality links than lesser developed countries, largely due to the availability of air conditioning, but not all communities have access to this option (Carleton et al., 2022). For example, outdoor workers exposed to extreme heat and wildfire smoke may not be able to take breaks indoors with air conditioning or consistently use protective equipment like masks. Finally, adaptation can be costly or resource intensive. For example, installing home air filtration systems to reduce risks from exposure to poor air quality or restricting development in the wildland–urban interfaces to reduce risks associated with wildfires require financial and policy resources.

might witness reductions in cold deaths (Lee and Dessler, 2023). On a population level, reductions in cold-related mortality could possibly be expected in a few regions under climate warming scenarios. Epidemiological studies that examine the number of deaths associated with cold have found conflicting results. For example, an analysis of U.S. mortality trends from 1999 to 2022 reported a 3.4% annual increase in age-adjusted cold-related mortality rates, with a sharp rise after 2017 (12.1% annually), suggesting that cold-related mortality has not uniformly declined over time (Liu et al., 2025). Methodological factors contribute to the complexity of assessing relative heat- and cold-related mortality data, including choices about the temperatures to use and the exposure-response relationship; for example, Alahmad et al. (2025) have noted that the area under the curve for heat is often smaller (for example only a third of the total area), contributing to observations of greater numbers of cold-associated death. The seasonality of cold-related deaths also corresponds to other factors beyond temperature, such as exposure to influenza, which increases in moderately cold and drier conditions, and to socioeconomic status (Ebi and Mills, 2013). Because multiple factors follow the same seasonal pattern as temperature, attribution of the observed increases in health impacts as temperature reach their coldest seasonal levels can be difficult. Evidence since EPA (2009a) strengthens association with adverse heat-related health consequences, while adding nuance around how changes to climate are anticipated to affect deaths from heat versus cold, suggesting a need for further research in this area to understand the balance of effects.

5.3 AIR QUALITY

Studies over the past 15 years have expanded the understanding of how climate change affects ozone and airborne particulate matter, and how exposure to these air pollutants negatively affects human health. In 2009, EPA concluded that "[t]he evidence concerning adverse air quality impacts provides strong and clear support for an endangerment finding" (EPA, 2009b, p. 66497). This conclusion was largely based on strong evidence that climate change is increasing ground-level (tropospheric) ozone concentrations. The report cited uncertainty in the directional effect on particulate matter. Since 2009, several assessments have documented the air quality impacts of climate change, with particular focus on ground-level ozone and particulate matter (see Section 3.5). Evidence supports the EPA (2009a) conclusion on ground-level ozone and has expanded understanding of the health impacts. For particulate matter, evidence now points to increases in atmospheric concentrations under climate change in some U.S. locations, especially in areas prone to wildfires and dust. Because exposure to these pollutants affects a range of health outcomes, including premature mortality, cardiovascular effects, and respiratory effects, climate-driven increases in ozone and particulate matter have deleterious health impacts.

Key authoritative assessments published since EPA (2009a) conclude that climate change worsens air pollution. For example, USGCRP (2023) concluded with medium confidence that air quality would worsen in many parts of the United States, with harm to human health and increased premature death being very likely (high confidence): "Extreme heat events, which can lead to high concentrations of air pollution, are projected to increase in severity and frequency (very likely, very high confidence), and the risk of exposure to airborne dust and wildfire smoke will increase with warmer and drier conditions in some regions (very likely, high confidence)" (p. 14–5). New research published since this assessment continues to support this conclusion. The sections below describe the current state of knowledge on ozone and particulate matter.

Many people are exposed simultaneously to multiple air pollutants, heat, pollen, and other climate-sensitive risk factors. In 2020, a systematic literature review found sufficient and moderate-quality evidence for synergistic effects of heat and air pollution (Anenberg et al., 2020). While limited evidence prevented conclusions from being drawn about synergistic effects from co-exposure to these risk factors with pollen, the authors concluded that "many disease states, including heart and lung disease, share a common pathway in which exposure to heat, air pollution, and pollen cause systemic and organ-specific inflammation and cellular damage." Since that review was published, additional studies have found that co-exposure to heat and air pollution had larger effects beyond the sum of their individual effects (Chen et al., 2024; Rahman et al., 2022; Rai et al., 2023; Stafoggia et al., 2023).

Ground-Level Ozone

EPA (2009a) concluded that climate change is expected to worsen ozone pollution across broad regions of the United States, increasing risks of respiratory illness, premature death, and ecological harm, even as the effects on particulate matter remain uncertain. Recent literature supports the EPA (2009a) conclusion regarding ground-level (tropospheric) ozone and adds a fuller understanding of the multiple drivers of ozone increases under climate change as well as harmful interactions with other exposures like heat and particulate matter. Climate change contributes to increases in ozone exposure on both short-term and long-term time scales (see Chapter 3).

Ozone exposure is associated with respiratory effects (EPA, 2020; Holm and Balmes, 2022), pre-term birth (Rappazzo et al., 2021), and premature mortality from all causes and from cardiopulmonary disease (Jerrett et al., 2009; Lim et al., 2019; Turner et al., 2016). Studies show that ozone concentrations tend to be higher in areas of the United States that are suburban, exurban, or rural; in wealthier neighborhoods; and in areas where a higher fraction of the population is non-Hispanic Asian or non-Hispanic White (Collins et al., 2022; Liu et al., 2021).

USGCRP (2016) concluded: "Climate change will make it harder for any given regulatory approach to reduce ground-level ozone pollution in the future as meteorological conditions become increasingly conducive to forming ozone over most of the United States [Likely, High Confidence]. Unless offset by additional emissions reductions of ozone precursors, these climate-driven increases in ozone will cause premature deaths, hospital visits, lost school days, and acute respiratory symptoms [Likely, High Confidence]" (p. 9).

Evidence since 2009 shows that long-term exposure to ozone has health effects beyond those from short-term exposure to ozone. Epidemiological studies increasingly show health effects associated with long-term ozone exposure, including chronic respiratory disease and premature mortality among adults and decreased lung function and lung function growth among children (Di et al., 2017; Hao et al., 2015; Holm and Balmes, 2022; Kazemiparkouhi et al., 2020; Lim et al., 2019; Turner et al., 2016). For example, a large prospective cohort of U.S. adults with 17 years of follow-up from 1995 to 2011 found that for each 10 parts per billion increase in the annual average 8-hour daily maximum ozone exposure, ischemic heart disease increased by 6% (95% confidence interval [2%, 9%]) and chronic obstructive pulmonary disease increased by 9% (95% confidence interval [3%, 15%]) (Lim et al., 2019).

Methane (CH_4) emissions also contribute to long-term ozone concentrations (see Chapter 2, Figure 2.2 for information on annual CH_4 emissions and Chapter 3 for discussion of climate effects on air quality) and to health impacts. An analysis led by the UN Environment Programme reported that every 10 million metric tons of CH_4 emissions leads to approximately 430 (approximately 290 to 550) premature respiratory deaths and approximately 330 (approximately 110 to 540) premature cardiovascular deaths in the United States attributable to ozone in persons aged 30 and older, along with approximately 150 respiratory hospitalizations and approximately 1,500 asthma-related accident and emergency department visits in the United States due to ozone exposure (UNEP and CCAC, 2021).

Taken together with evidence of conditions favorable to creating more ozone pollution (see Chapter 3), this evidence supports the EPA (2009a) conclusion that GHGs and climate change exacerbate ozone pollution, adversely affecting health in the United States. Furthermore, the new evidence adds context to that understanding, including climate-sensitive drivers of ozone pollution, and shows that health outcomes are amplified by climate-driven increases in co-occurrence of ozone exposure with heat and particulate matter exposure, and by synergistic health effects from these multiple exposures.

Particulate Matter

EPA (2009a) found that "the directional effect of climate change on ambient particulate matter levels remains uncertain" (p. ES-5). Since 2009, evidence has shown that climate change is altering particulate matter levels across the United States, with climate-driven increases in the western United States due to increased wildfire smoke and dust.

Fine particulate matter, or $PM_{2.5}$, referring to particles that are 2.5 microns or smaller in diameter, are solid and liquid particles that can penetrate deeply into the human lung and affect a wide range of biological systems. $PM_{2.5}$ is a mixture of chemical components that varies geographically, mainly driven by local emission sources and atmospheric transport of air pollution regionally. Major components include black carbon, organic carbon, nitrate, sulfate, ammonium, and metals and other trace elements. The EPA has found $PM_{2.5}$ to be causally associated with cardiovascular effects and mortality and likely to be causally associated with respiratory effects, nervous system effects, and cancer (EPA, 2022). Many studies show that $PM_{2.5}$ is inequitably distributed, with communities with lower income and higher proportions of non-White populations most exposed (Colmer et al., 2020; Jbaily et al., 2022; Ma, Zang, Opara et al., 2023).

USGCRP (2016) found that climate change is expected to alter several meteorological factors that affect $PM_{2.5}$. Factors that are expected to increase $PM_{2.5}$ include increased humidity, increased stagnation events, and increased biogenic emissions. Factors that are expected to decrease $PM_{2.5}$ include increases in precipitation and enhanced atmospheric mixing. The USGCRP report also found links between climate change and increased frequency and length of wildfires and wildfire seasons, with associated emissions and harmful impacts on health. It found that "wildfires may dominate summertime $PM_{2.5}$ concentrations, offsetting even large reductions in anthropogenic $PM_{2.5}$ emissions" (p. 77). Climate change has been projected to increase drought in some regions, which can also lead to more airborne dust exposure. USGCRP (2023) similarly found that most known climate-related drivers of $PM_{2.5}$ increase concentrations, including wildfires, heat waves, temperature, drought, biogenic emissions, and humidity, and that more precipitation would lower $PM_{2.5}$ levels, as precipitation is a main removal mechanism of $PM_{2.5}$ from the air. However, to date there is no consensus on the impacts of climate-driven changes in regional transport and stagnation on $PM_{2.5}$.

Wildfires

EPA (2009a) found that "In some regions, changes in the mean and variability of temperature and precipitation are projected to increase the size and severity of fire events, including in parts of the United States" (p. 86), noting that "Increase in wildfire frequency associated with a warmer climate has the potential to increase PM levels in certain regions" (p. 94). While EPA (2009a) addressed impacts of wildfires on welfare, it did not expand on the health impacts of wildfires in detail. Since 2009, a large body of literature has developed on climate change-driven variations in wildfire smoke exposure and associated health impacts in the United States. See Chapter 3 for a discussion of wildfire trends and variability, including an increase in burned acreage in the West.

The presence of more wildfires across the U.S. landscape and wildfire smoke in the skies is one condition that has affected the United States with more severity and scope than expected since 2009. Wildfires threaten health directly—through injuries, burns, and heat exposure—and indirectly, through smoke-related respiratory illness and trauma-related mental health harms (Gould et al., 2024; Lei et al., 2024; Ma, Zang, Liu et al., 2023).

These health impacts are felt in communities directly affected by the fire and first responders such as wildfire fighters, as well as in distant locations, as smoke can travel across state and even national boundaries. Wildfire smoke contributes to both short-term health outcomes from acute exposures and chronic health outcomes from long-term average $PM_{2.5}$ concentrations. Wildfires affect air quality as extreme episodic events and as contributors to everyday exposures (Gould et al., 2024).

USGCRP (2016) concluded, "Wildfires emit fine particles and ozone precursors that in turn increase the risk of premature death and adverse chronic and acute cardiovascular and respiratory health outcomes (Likely, High Confidence). Climate change is projected to increase the number and severity of naturally occurring wildfires in parts of the United States, increasing emissions of particulate matter and ozone precursors and resulting in additional adverse health outcomes (Likely, High Confidence)" (p. 85). As the literature continued to build, the USGCRP (2023) concurred with the 2016 report that climate change contributes to more frequent and severe wildfires that worsen air quality in many regions, while noting that "Although large challenges remain, new communication and mitigation measures are reducing a portion of the dangers of wildfire smoke (medium confidence)" (p. 14–9).

Wildfires release a complex mix of particulate matter, carbon monoxide, nitrogen oxides, and volatile organic compounds that can harm human health. Wildfire-specific particulate matter likely has a different chemical profile compared with particulate matter originating from other sources, and exposure to $PM_{2.5}$ from wildfire smoke has been reported to be more harmful to health than $PM_{2.5}$ from other types of sources, although more research is needed to understand this differential toxicity (Aguilera et al., 2021; Alari et al., 2025; Gould et al., 2024). Wildfire smoke from fires in urban and industrial areas and the wildland–urban interface can also contain toxic metals such as lead and mercury, plasticizers, and other pollutants (NASEM, 2022). Wildfire smoke has also been documented to contain carcinogens such as benzene, benzo[a]pyrene, hexavalent chromium, and dibenz[a,h]anthracene (Naeher et al., 2007). As a recent review noted, "The amount and composition of pollution emitted from a specific fire vary depending on the fire's size, temperature of combustion, materials burned (e.g., grasses, tree species, buildings, vehicles), distance the smoke has traveled, and environmental conditions like wind speed, temperature, and humidity" (Gould et al., 2024, p. 279; Montrose et al., 2022).Consistent with these prior assessments, new studies find that wildfires are offsetting reductions in anthropogenic $PM_{2.5}$ emissions over the western United States and increasing daily cumulative smoke $PM_{2.5}$ exposure for the average person in the United States compared with the 2006–2019 average (Lancet Countdown, 2024; Wei et al., 2023). The number of people in the United States who have experienced at least 1 day with wildfire smoke $PM_{2.5}$ >100 $\mu g\ m^{-3}$ (micrograms per cubic meter) has significantly increased, with about 25 million people exposed in 2020 (Childs et al., 2022).

Observational studies indicate that exposure to wildfire smoke, like exposure to air pollution from other sources, is associated with a spectrum of adverse health outcomes. Substantial literature documents wildfire smoke's impacts on respiratory health (Zhou et al., 2021). Gould et al. (2024) found that "same-day all-cause mortality increased by 0.15% (95% confidence interval [CI] 0.01–0.28%) per 1-$\mu g\ m^{-3}$ increase in wildfire-specific $PM_{2.5}$. There were robust positive associations between wildfire $PM_{2.5}$ and same-day respiratory outcomes: Respiratory hospitalizations increased by 0.25% (95% CI 0.09–0.52%) and respiratory ED [emergency department] visits increased by 0.36% (95% CI 0.19–0.53%) per additional 1-$\mu g\ m^{-3}$ increase in ambient wildfire smoke $PM_{2.5}$. [Gould et al.] found a non–statistically significant 0.06% (95% CI 0.00–0.12%) increase in same-day cardiovascular hospitalizations and no meaningful change in same-day cardiovascular ED visits (–0.03%; 95% CI –0.18–0.12%) per additional 1-µg m^{-3} increase in ambient wildfire smoke $PM_{2.5}$. For all outcomes except respiratory hospitalizations and cardiovascular ED visits, there was evidence of heterogeneity in effects across studies (i.e., Q-statistic $p < 0.05$)" (p. 282).

Research is also associating exposure to wildfires with negative pregnancy and birth outcomes, such as pre-term birth, potentially through the effects of both maternal stress from experiencing the wildfire and exposure to wildfire smoke (Heft-Neal et al., 2022). Exposure to wildfire smoke has also been associated in recent literature with declines in mental health and to worsened cognitive outcomes (Eisenman and Galway, 2022; Xu et al., 2020). Wildfire smoke can spread spores and microbes that contribute to fungal disease and antimicrobial resistance (Mulliken et al., 2023; Salazar-Hamm and Torres-Cruz, 2024). New research also indicates that wildfire smoke exposure may contribute to skin diseases, eye conditions, and cancer.

One study estimated that of 164,000 estimated wildfire $PM_{2.5}$-related deaths over 15 years in the United States, about 10% (or 15,000) were linked with climate change-driven increases in wildfire. These premature deaths from climate change-driven increases in wildfire smoke translated to a cumulative economic burden of $160 billion. More than one-third of the climate change-driven $PM_{2.5}$ deaths occurred in 2020, with monetized damages of $58 billion (Law et al., 2025). Another study estimated that long-term exposure to carbonaceous $PM_{2.5}$ from fire smoke led to 7,455 (95% CI [6,058, 8,852]) premature deaths across the continental United States each year, with monetized damages of $68.3 billion (95% CI [$31.9 billion, $104.0 billion]) (Jin et al., 2025).

Dust

EPA (2009a) found that "[particulate matter] and [particulate matter] precursor emissions are affected by climate change through physical response (windblown dust), biological response (forest fires and vegetation type/distribution), and human response (energy generation). Most natural aerosol sources are controlled by climatic parameters like wind, moisture, and temperature; thus, human-induced climate change is expected to affect the natural aerosol burden" (p. 94). Since 2009, evidence linking climate change with increased airborne soil dust and associated health effects has continued to build, particularly for areas that are warmer and drier, such as the Southwest United States (see Section 5.5 on climate sensitive diseases).

Dust is a component of particulate matter in the air and is a key contributor to PM_{10}, or particles 10 microns or smaller in diameter (NASEM, 2025). Major emission sources include soil entrainment into the air and anthropogenic activities, such as road and vehicle tire wear. Climate change in other world regions can impact dust concentrations over the United States, as dust from African deserts reaches the Caribbean and dust from Asia reaches the western United States and Hawaii (Rosas et al., 2025; Yu et al., 2019). Dust exposure can lead to a variety of deleterious health outcomes, including premature death, allergies, asthma attacks, and respiratory infection. A large scoping review found that among 204 epidemiological studies, over 80% reported positive associations between dust and adverse health outcomes (Lwin et al., 2023).

USGCRP (2016) concurred with the EPA (2009a) statement, finding that "climate-driven changes in meteorology can also lead to changes in naturally occurring emissions that influence air quality (for example, wildfires, wind-blown dust, and emissions from vegetation)" (p. 71). USGCRP (2023) also concluded in Key Message 14.1 that "the risk of exposure to airborne dust and wildfire smoke will increase with warmer and drier conditions in some regions (very likely, high confidence)" (pp. 14–5). These findings for the United States are consistent with the 2024 Report of the Lancet Countdown on Health and Climate Change that has a global scope. As part of that effort, the report found that "The hotter and drier weather conditions are increasingly favoring the occurrence of sand and dust storms" (Romanello et al., 2024). Recent studies build on earlier findings around how climate change affects dust concentrations in parts of the United States and provide more information about contributions of different climate-sensitive drivers. In a historical, observational study, Achakulwisut et al. (2018) found that drought and soil dryness were key drivers of increased fine dust over the Southwest United States, with 0.22–0.43 µg m^{-3} increase in fine dust for each unit increase in the 2-month Standardized Precipitation-Evapotranspiration Index, an indicator of soil dryness.

Climate change can also lead to more entrainment of dust from exposed lakebeds into the air (NASEM, 2020, 2025; West et al., 2023). Changing precipitation patterns, higher temperatures, persistent droughts, less water inflow from reduced snowpack, and increased evaporation, among other climate-sensitive conditions, can result in lower water levels for lakes in parts of the United States, such as the Great Salt Lake (Baxter and Butler, 2020). With a larger area of exposed lakebed, more dust can become entrained into the air, exposing people in nearby communities and across a broader area (Grineski et al., 2024). Lakebed dust often contains metals, pathogens, and other health-harmful agents (Putman et al., 2025). More exposure to lakebed dust could result in a variety of health outcomes, with potentially higher risks for children (Putman et al., 2025). Evidence on the relative contributions of climate change and water management practices to declining lake levels is limited and differs across lakes.

Indoor Air

Impacts of climate change on indoor air quality were not directly addressed in EPA (2009a). Indoor air quality is affected by outdoor air coming in, contaminants generated indoors (e.g., mold, dust mites, volatile organic compounds and other chemicals off gassing from building materials, indoor combustion), indoor temperatures, and other factors (NASEM, 2024d). As Americans spend most of their time indoors (Klepeis et al., 2001), changes in indoor air quality can have important effects on public health.

USGCRP (2016) identified climate impacts on indoor air quality as an emerging issue. The report highlighted multiple pathways through which climate change can negatively affect indoor air quality, including worsening outdoor air pollution that infiltrates indoors; altered patterns of indoor–outdoor air exchange; and more favorable conditions for growth and spread of pests, infectious agents, and disease vectors. Evidence showing negative impacts of climate change on indoor air quality has continued to build since the 2016 report, particularly related to indoor air quality during wildfire smoke events, mold driven by building dampness, and climate sensitivity of pollutants originating indoors.

Indoor exposure to wildfire smoke is a concern, especially as common public health messaging during wildfire smoke events is to stay indoors. USGCRP (2023) found that "Research investigating indoor concentrations during wildfire smoke events is preliminary, and there is a specific need to understand how indoor concentrations vary between socioeconomic groups during wildfire smoke events" (pp. 14–23). Recent studies show that volatile organic compounds from wildfire smoke can persist indoors for days after the smoke event (Dresser et al., 2024; Li et al., 2023), and that smoke and other forms of outdoor air pollution increase indoor $PM_{2.5}$ levels, particularly in lower income areas (Krebs and Neidell, 2024). Wildfire smoke exposure and increased indoor crowding to avoid outdoor smoke is also associated with increased risk of infection from viruses (Arregui-García et al., 2025; Mahendran et al., 2025; Orr et al., 2025), such as influenza and COVID-19.

Climate change can also influence indoor air quality from pollutants originating indoors. Rain, flooding, and humidity changes affect building dampness, leading to mold and other microbial agents that increase risk of allergic rhinitis, asthma, and other respiratory conditions (Eguiluz-Gracia et al., 2020; WHO, 2009). Increased temperature and humidity can alter rates of chemical off-gassing from building and furniture materials, as well as chemical reaction rates, both of which influence levels of indoor air pollutants (Abbat and Wang, 2020; Salthammer and Morrison, 2022).

These potential impacts of climate change on indoor air quality likely differ across households and other buildings, driven by geographic and building-specific factors such as building codes, building materials, presence of air filtration devices, and climate control, making it challenging to evaluate the combined impact of the effects described here for different locations (Mansouri et al., 2022).

Air Quality Impacts from Co-emitted Pollutants

Fossil fuel combustion leads to emissions of both carbon dioxide (CO_2) and co-emitted particulate matter and ozone and particulate precursors that directly affect air quality (NASEM, 2024a; USGCRP, 2023). Information about air quality and health co-benefits from reduced fossil fuel combustion was building in 2009 (Bell et al., 2008), and since that time has expanded with many quantified and monetized estimates of co-benefits from reducing fossil fuel combustion in power, residential, transportation, and other sectors (Balbus et al., 2015; Buonocore et al., 2016; Garcia et al., 2023; Levy et al., 2016; Sergi et al., 2020). For example, a review of the health impacts during the first 6 years of the Regional Greenhouse Gas Initiative—a policy that reduced GHG emissions in the Northeast and Atlantic regions of the United States—found that "These benefits include hundreds of avoided cases of premature deaths, heart attacks, asthma attacks, and hospital admissions, and tens of thousands of avoided cases of other health symptoms, lost work days, and restricted activities" (Manion et al., 2017, p. 38). Several studies project that future economic benefits associated with avoiding health effects of co-emitted pollutants are substantial (e.g., McDuffie et al., 2023; Shindell et al., 2024; West et al., 2023).

5.4 ADDITIONAL EXTREME WEATHER EVENTS

Extreme weather events contribute to injury and illness, exacerbate chronic disease, and affect mental health (Ebi et al., 2021; USGCRP, 2016). The occurrence of extreme weather events can also disrupt critical infrastructure and health care systems, reducing access to care, disrupting supply chains, and contributing to mortality (Salas et al., 2024).

Chapter 3 discusses the ways that climate change is affecting extreme weather. This section addresses health effects associated with extreme weather events, noting that it is challenging to attribute health impacts from individual weather events to climate change. Determining how climate change influences any single weather or climate event requires accounting for multiple natural and human factors (NASEM, 2016), and the health effects associated with any event also can be affected by multiple factors.

Droughts

Droughts are projected to become more frequent, longer lasting, and more severe across some regions of the United States (Martin et al., 2020; Overpeck and Udall, 2020; Tripathy et al., 2023). Research has linked drought to health consequences including higher risks of respiratory, cardiovascular, and all-cause mortality in several U.S. regions, particularly among older adults, women, and rural residents (Abadi et al., 2022; Gwon et al., 2023, 2024, 2025; Salvador et al., 2023). Drought compounds the health risks of other extreme events such as heat waves and dust storms (Leeper et al., 2025) and combined drought–heat events have been associated with increased mortality in people with chronic lung disease (Rau et al., 2025). Beyond physical health, drought contributes to mental and occupational health risks, with studies showing greater stress among farmers during drought years (Berman et al., 2021). Climate change and drought also impact water quality (see discussion in Chapter 6).

Hurricanes

Globally, the share of hurricanes reaching the most intense categories has increased over the past four decades, and although landfalls in the United States have not increased, there is emerging evidence that U.S. hurricanes are moving more slowly at landfall, producing heavy rainfall, damaging wind, and coastal flooding (see discussion in Chapter 3). Several studies have analyzed the mortality associated with hurricanes. For example, an analysis of two approaches found that Hurricane Maria was responsible for 1,191 excess deaths using census population data, and 2,975 excess deaths (95% CI [2,658, 3,290]) from September 2017 to February 2018 when accounting for demographic shifts that had also taken place over that time (Santos-Burgoa et al., 2018). Effects can persist for a prolonged period after the event itself; a modeling study examining longer-term, indirect effects of tropical cyclones on mortality in the United States estimated that the average tropical storm contributed 7,000 to 11,000 excess deaths (Young and Hsiang, 2024). The study also examined 501 historical storms between 1930 and 2015 and estimated a tropical cyclone-related mortality burden of 3.2–5.1% of all deaths in the Atlantic coastal region between 1930 and 2015 (Young and Hsiang, 2024). Evidence shows an increase in the average number of deaths per tropical cyclone in the United States since 2001, due to a combination of storm factors, shifting of population spatial distribution towards coastal areas, and demographic trends. Young and Hsiang (2024) found no evidence of adaptation reducing the deadliness of these storms.

Floods

Floods are associated with human health impacts, as described below. Many non-climate factors contribute to the risks to human health from floods, such as emergency preparedness and response and the location and condition of infrastructure. Changes in heavy precipitation and sea level rise associated with climate change (see Chapter 3) may also contribute to the risk. A recent global analysis of flood fatalities by Jonkman et al. (2024) found that no trend in flood-related mortality has been observed.

Extreme rainfall and flooding have been linked with hospital admissions and adverse health outcomes, including increased risk of injury, infectious diseases, increased morbidity and mortality from cardiovascular disease and other causes (Aggarwal et al., 2025; He et al., 2024; Lynch et al., 2025; Wettstein et al., 2025). Floods can also damage or impede access to critical infrastructure including hospitals, disrupt medical supply chains, and cut people off from care (Wu et al., 2024). For example, a Veterans Affairs hospital closed for six months after Hurricane Sandy, and the study found that the "temporary period of decreased access to health care services was associated with increased rates of uncontrolled hypertension, but not with increased rates of uncontrolled diabetes or hyperlipidemia, more than 1 year after the Manhattan VA facility reopened" (Baum et al., 2019, p. 2 of 13). More than 700 hazardous waste sites are located in high-risk flood zones, increasing concerns about exposure to toxic chemicals (GAO, 2019). Beyond physical illness and death, exposure to floods can contribute to adverse pregnancy outcomes and leave lasting mental health impacts, especially for children (Wu et al., 2024).

5.5 CLIMATE-SENSITIVE DISEASES

EPA (2009a) noted that many human diseases were sensitive to weather and the USGCRP (2016) report on climate and health subsequently stated with high confidence levels that climate change is harming human health by increasing morbidity and mortality. As discussed above, exposure to increased heat and worsened air quality contributes to negative health outcomes. The effects of changing climate on the distribution of vector-borne disease effects are briefly described in this section. The effects of exposure to changing temperatures, weather events, increased $PM_{2.5}$, and allergens on a variety of chronic and noncommunicable diseases are also briefly discussed.

Vector-Borne Diseases

Climate suitability for various climate-sensitive pathogens and disease vectors has increased since EPA (2009a). Ticks can carry many diseases, including alpha-gal syndrome, Lyme disease, Babesiosis, Rocky Mountain spotted fever, and others. An increase in the geographic distribution of tick-borne diseases, anticipated in the 2009 report, has been observed and attributed to climate warming. Persistently warming temperatures may not only expand their geographic range but also extend their active season (USGCRP, 2016). One example is the lone star tick, which carries alpha-gal syndrome (inducing meat allergy) and has dramatically increased its U.S. distribution due to warming (Molaei et al., 2019). Similarly, Lyme disease—another tick-borne disease described in the 2009 EPA report—has expanded its range and activity due to climate warming with expansion in the northern United States and decreased southern activity, recognizing also that multiple factors interact to drive disease transmission (Couper et al., 2021; Kugeler et al., 2015; USGCRP, 2016). Lyme disease case report maps from the Centers for Disease Control and Prevention show range expansion from 1995 to 2023[2] with Lyme disease cases increasing from approximately 23,000 in 2002 to more than 62,000 in 2022 (CDC, 2004; Kugeler et al., 2024). Couper et al. (2021) examined Lyme disease incidence and found that the clearest climate–Lyme disease signal was observed in the Northeast United States, where rising annual temperatures were associated with higher incidence and a high-emissions scenario projected that there could be an estimated 23,619 ± 21,607 additional cases by 2050; however, this projection had uncertainty and no significant increases in disease incidence were projected for other regions. Couper et al. (2021) also found no significant increases or decreases in Lyme disease across any region under a

[2] See https://www.cdc.gov/lyme/data-research/facts-stats/lyme-disease-case-map.html (accessed September 8, 2025).

moderate-emissions scenario, underscoring the multifactor and regionally variable relationship between climate change and Lyme disease dynamics.

Dengue, a mosquito-borne viral disease, has increased in geographic range since EPA (2009a), now appearing in non-travelers in Texas, Florida, Arizona, California, and Hawaii.[3] This shift coincides with increased mosquito vector activity due to climate warming (Ebi and Nealon, 2016). With rising temperatures, the aggressive Asian tiger mosquito (*Aedes albopictus*) has expanded in the United States, raising concerns about potential outbreaks of diseases from Chikungunya and Zika viruses (Rochlin et al., 2013). Mordecai et al. (2019) has described how temperature affects both mosquito biting behavior and transmission of pathogens. West Nile disease, which is also mosquito-borne, has also been seen in the United States since the 2009 report, related to changes in precipitation and heat (Hahn et al., 2015).

Fungal Diseases

Fungal infection is expanding across the United States, particularly in western states (Salazar-Hamm and Torres-Cruz, 2024). Soil dust contains a variety of microorganisms, including bacteria and fungi. Recent studies show association between airborne soil dust or dust storms and Valley fever (Howard, Sayes et al., 2024; Tong et al., 2017). Valley fever, or coccidioidomycosis, is a fungal infection resulting from breathing *Coccidioides* fungal spores; it can cause fever, cough, fatigue, shortness of breath, and other symptoms; its incidence has increased from approximately 2,000 cases in 1998 to 21,000 cases in 2023[4] and its area of endemicity has expanded to include 12 states: Arizona, California, Colorado, Idaho, Kansas, Nebraska, Nevada, New Mexico, Oklahoma, Texas, Utah, and Washington (Gorris et al., 2019). In addition, changing weather patterns can affect *Coccidioides* growth and dispersal, as the fungus grows in the soil after heavy rainfall and disperses into the area in subsequent hot and dry conditions (Head et al., 2022).

Evidence also points to changes in geographical extent of histoplasmosis, the most frequent fungal respiratory infection in the United States The causative agent, *Histoplasma capsulatum*, is a dimorphic soil-based fungus endemic to the U.S. Midwest, Latin America, Africa, South Asia, and the Caribbean. Approximately 60–90% of people living in areas surrounding the Ohio and Mississippi river valleys have been exposed to *Histoplasma*.[5] Symptoms include fever, chills, headache, muscle aches, fatigue, and cough.[6] Histoplasmosis affects people who are immunosuppressed more severely. While histoplasmosis is far less studied than Valley fever, the area of endemicity in the United States is spreading northwest to Minnesota, Wisconsin, Michigan, Montana, and Nebraska (Hepler et al., 2022; Maiga et al., 2018).

Antimicrobial Resistance

EPA (2009a) did not address antimicrobial resistance as a climate-sensitive issue. Antimicrobial resistance causes significant global morbidity, with projections estimating 8.2 million annual deaths associated with antimicrobial resistance by 2050 (Naghavi et al., 2024). Several studies show that higher temperatures accelerate bacterial growth, mutation rates, and gene transfer, increasing resistance risk to antibiotics (McGough et al., 2020; Van Eldjik et al., 2024). Heat waves and droughts concentrate antibiotics and resistant bacteria in water systems, enhancing opportunities for developing resistance, while extreme rainfall spreads antibiotic-resistant pathogens from sewage and farms where antibiotics are used for animal health (MacFadden et al., 2018). Better understanding of this area and its potential intersections with climate change continues to be a topic of exploration.

[3] See https://www.cdc.gov/dengue/outbreaks/2024/index.html.

[4] See reported cases of Valley fever at https://www.cdc.gov/valley-fever/php/statistics/index.html (accessed September 8, 2025).

[5] See https://www.cdc.gov/histoplasmosis/php/statistics/?CDC_AAref_Val=https://www.cdc.gov/fungal/diseases/histoplasmosis/statistics.html.

[6] See https://www.lung.org/lung-health-diseases/lung-disease-lookup/histoplasmosis/symptoms-diagnosis.

Waterborne Diseases

Heavy precipitation and drought are linked to waterborne disease outbreaks. Excessive rainfall mobilizes pathogens into water supplies, while droughts disrupt sanitation. Contrary to the 2009 report's claim that flood-related infectious disease risks are low in high-income countries (EPA, 2009a), recent studies show heavy precipitation increases gastrointestinal illnesses in the United States (De Roos et al., 2020; Haley et al., 2024). Hurricanes and extreme weather events can also introduce pathogens into water systems via disrupted sanitation infrastructure. For example, *Vibrio parahaemolyticus* is a waterborne bacterium that causes seafood-associated diarrheal disease in the United States, while *Vibrio vulnificus* is also found in marine settings and causes serious wound infections and diarrheal illness. Increasing water temperatures and other changes to coastal waters caused by climate are predicted to enhance Vibrio replication with resultant increased infection from contaminated shellfish or wound exposure to contaminated water (Hayden et al., 2023; Schets et al., 2025; USGCRP, 2016). Extension northward along the East Coast and increases in the numbers of reported non-foodborne cases of *Vibrio vulnificus* since 1988 have been observed (Archer et al., 2023; Brumfield et al., 2025).

Moreover, as water temperatures rise and more humans use recreational water due to heat, increasing infections with *Naegleria fowleri*, a thermophilic ameba that causes meningoencephalitis, is possible as well as a northward expansion of this disease (Heilmann et al., 2024; USGCRP, 2016). The potential for exposure to toxins associated with harmful algal blooms is another potential impact on health (see Chapter 6).

Noncommunicable Diseases

Exposure to heat, ozone, particulate matter, and extreme events also impact several noncommunicable and chronic diseases associated with the cardiovascular, renal, and pulmonary systems. The potential impacts extend to psychological and mental health and nutrition, areas not addressed in EPA (2009a).

Cardiovascular health: Cardiovascular diseases are the world's leading cause of disability and death. In 2022, 941,652 U.S. deaths were attributable to cardiovascular disease for all ages (Martin et al., 2025). Pollution has had a major impact on cardiovascular morbidity and mortality. Short-term variation in $PM_{2.5}$ levels (from hours to days) is associated with increased risks of myocardial infarction, stroke, and death from cardiovascular disease (Rajagopalan and Landrigan, 2021). During heat waves, a meta-analysis of 266 papers found the risk of cardiovascular disease-related mortality increased by 11.7% (95% CI [9.3, 14.1%]) with the risk increasing as heat wave intensity increased (Liu et al., 2022). Both hot and cold temperature extremes increase risk; an analysis of cardiovascular-related deaths across 27 countries including the United States found that "hot days (above 97.5th percentile) and cold days (below 2.5th percentile) accounted for 2.2 (95% empirical CI [eCI], 2.1-2.3) and 9.1 (95% eCI, 8.9-9.2) excess deaths for every 1000 cardiovascular deaths, respectively" (Alahmad et al., 2023). There are several mechanisms for how extreme temperature impacts the cardiovascular system. Heat, for example, strains the cardiovascular system (e.g., dehydration, hypotension, tachycardia, electrolyte shifts). People with heart failure, coronary disease, or arrhythmia are at highest risk; certain drugs (e.g., β-blockers, antiplatelets) can impair heat loss or increase heat-myocardial infarction (MI) risk (Chen et al., 2022). The risk has often been found to be higher in susceptible subgroups, including older people, people with preexisting conditions, and those who are socioeconomically disadvantaged (Singh et al., 2024). Heat waves and factors such as ground-level ozone that worsen air quality are associated with higher rates of cardiovascular mortality (Kazi et al., 2024). Exposure to $PM_{2.5}$ components, emissions from fossil fuels, and chemical combustion by anthropogenic sources (e.g., gas stations) are associated with increased hypertension (Chen et al., 2025; Xu et al., 2022), another risk factor for cardiovascular morbidity. It has been calculated that for every increment of 10 $\mu g\ m^{-3}$ in $PM_{2.5}$, the risk of myocardial infarction, stroke, or cardiovascular-related death increases 0.1–1%, and air pollution is estimated to contribute to 14% of all stroke-associated deaths (Rajagopalan and Landrigan, 2021; Verhoeven et al., 2021). A meta-analysis of 35 studies showed "increases in particulate matter concentration were associated with heart failure hospitalisation or death ($PM_{2.5}$ 2.12% per 10 $\mu g/m^3$, 95% Confidence Interval 1.42-2.82; PM_{10} 1.63% per 10 $\mu g/m^3$, 95% Confidence Interval 1.20-2.07). Strongest associations were seen on the day of exposure, with more persistent effects for $PM_{2.5}$. In the USA, we estimate that a mean reduction in $PM_{2.5}$ of 3.9 μg/m^3 would prevent 7,978 heart failure hospitalisations and save a third of a billion U.S. dollars a year" (Shah et al., 2013, p. 1,039). Air pollution has also been associated with an increased risk of atrial fibrillation and ventricular arrhythmias (Peralta et al., 2020).

Renal health: Extreme temperatures can increase the risk of heat stroke and dehydration leading to heat exhaustion, hypotension, and acute kidney disease (Glaser et al., 2016). There has also been a recent increase in chronic kidney disease of unknown etiology in rural communities, particularly in outdoor working farmworkers, in different parts of the world with increased temperatures and decreased rainfall (Glaser et al., 2016). A current hypothesis suggests that heat along with occupational exposures plays a role in this recent epidemic of unexplained chronic kidney disease in MesoAmerica and Sri Lanka (Hansson et al., 2023; Johnson et al., 2019; Wijkström et al., 2013). Studies are now ongoing looking for the cause of unexplained increased renal disease in agricultural workers in the central valley of California, with a hypothesis that extreme heat is an underlying factor (Bragg-Gresham et al., 2020).

Pulmonary health: Climate change is associated with increased risk factors for respiratory health. This linkage was noted in EPA (2009a); however, the extent of impact was not fully explored. Air pollutants and extreme temperatures have been associated with an increased risk of chronic obstructive pulmonary disease (COPD) and asthma exacerbations and higher mortality rates from these respiratory diseases (Almetwally et al., 2020). Various components of air pollution have been associated with worsened lung function, asthma exacerbations, and COPD, including $PM_{2.5}$, nitrogen dioxide, and tropospheric ozone (Vongelis et al., 2025). Wildfire smoke—particularly $PM_{2.5}$—is strongly associated with increased emergency department visits and hospitalizations for respiratory illnesses such as asthma (McArdle et al., 2023). Particularly susceptible populations include children, adults over the age of 65, pregnant women, and people in areas where access to climate adaptation and health care may be compromised (Covert et al., 2023).

Psychological and mental health: The climate's impact on mental health was not addressed in EPA (2009a). Extreme weather events have been associated with increased rates of anxiety, depression, and mental health disorders (Barbani, 2025). Air pollution ($PM_{2.5}$) has been associated with increased prevalence of mood and psychotic disorders (e.g., schizophrenia) and suicide (Hoare et al., 2019; Kim et al., 2018; Newbury et al., 2019). Heat waves and high temperatures are associated with increased cases of suicide, hospital visits for mental health issues, crime, and violence (Choi et al., 2024; Mahendran et al., 2021; Nori-Sarma et al., 2022; Thompson et al., 2023). Sleep (particularly deep sleep) is also affected by ambient temperature and humidity, which may be impacted by climate warming, and can further exacerbate mental health declines (Li et al., 2025; Okamoto-Mizuno and Mizuno, 2012). Growing evidence also shows that long-term exposure to air pollution may play a role in dementia (Abolhasani et al., 2023; Best Rogowski et al., 2025). Studies have shown increased anxiety among children and youth around climate change. A global study of 10,000 youth and young adults in 10 countries found that 59% reported being extremely worried about climate change, and more than 50% reported negative emotions such as sadness, anxiety, anger, helplessness, and powerlessness (Hickman et al., 2021). Lastly, one should note the many psychological impacts from events that displace people from their homes (Bellizzi et al., 2023).

Nutrition and food safety: Impacts on nutrition were also not addressed in EPA (2009a). There are several pathways by which climate change impacts nutrition and food safety. The rise in temperatures and variability in precipitation amount and intensity have negatively affected agricultural production. (See Chapter 6 for more detailed discussion of food production and agriculture.) Such events strain global food systems (Romanello et al., 2021) and can affect crop frequency (number of production seasons per year) and caloric yields (crop yield in calories produced per acre). Food safety is also threatened by increased warming. The IPCC report (2022a) noted that increasing temperature accelerated the growth of foodborne pathogens like Salmonella and Campylobacter. Warmer conditions extend the survival of pathogens in soil, and water and food supplies. Alterations to marine ecosystems can disrupt marine food supplies in some communities (USGCRP, 2023). Elevated atmospheric CO_2 concentration is associated with lower nutritional value in staple crops. Myers et al. tested several crops from different countries including the United States and found a significant decrease in the concentration of iron and zinc in C_3 (cool season) grasses and legumes (Myers et al., 2014). Zinc and iron deficiencies increase the risk of infections, diarrhea, and anemia. These sequelae would be more impactful in low resourced settings globally or in malnourished children in the United States. Although CO_2 concentrations can increase plant growth with potential effects on crop yields (see discussion in Chapter 6), the IPCC 2023 Synthesis Report noted that these benefits are often offset by climate related stresses such as heat, drought, and nutrient limitations.

Diseases Caused by Airborne Allergens

As reported in EPA (2009a), multiple factors influence allergen levels and health consequences such as allergies and asthma, including changes to CO_2 and climate that affect plant growth, distribution, and allergenicity. Evidence since 2009 continues to indicate that GHGs and associated climate changes affect airborne allergens in ways that can contribute to allergies and asthma, while recognizing that development of such conditions depends not only on environmental exposures but also on individual and genetic factors (Dharmage et al., 2019).

USGCRP (2023) reported that factors such as rising temperatures, changes in precipitation, elevated CO_2, and higher ozone levels are affecting pollen, with effects than can include extending pollen seasons, boosting pollen levels, and broadening the geographic range of allergenic plants, while enhancing pollen allergenicity (Agache et al., 2024; Anderegg et al., 2021; Epstein et al., 2025; Lee et al., 2023; Paudel et al., 2021; USGCRP, 2023; WHO, 2018; Zhang and Steiner, 2022). For instance, ragweed pollen season in parts of the United States grew longer by as much as 13 to 27 days between 1995 and 2009 (Ziska et al., 2011). Increases in rainfall and flooding associated with climate change can also foster mold growth and facilitate the introduction of new allergenic species (Epstein et al., 2025). Extreme weather can worsen respiratory risks. Thunderstorms can rupture pollen grains, leading to "thunderstorm asthma," associated with increases in asthma events (Agache et al., 2024; Beggs, 2024; D'Amato et al., 2016; Mampage et al., 2022), with a recent analysis finding a 24% increased risk (95% CI [13, 36%]) (Makrufardi et al., 2023). Post-disaster studies of hurricanes have found increased mold and endotoxin exposures and mold reactivity, especially among those with asthma (Chew et al., 2006; Rao et al., 2007; Sampath et al., 2023). Wildfire smoke, dust, and sandstorms can alter pollen structure, increasing allergenicity and inflammation and amplifying allergic and respiratory diseases (WHO, 2025). Drier, hotter conditions may intensify airway inflammation, while air pollution increases allergic inflammation and susceptibility to viral infections (Burbank, 2025; Edwards et al., 2025; Wright and Demain, 2024).

Elevated atmospheric CO_2 concentration leads to more vigorous growth in many plant species, which often results in increased pollen production. Research on allergenic plants, such as ragweed, has demonstrated that higher CO_2 levels cause them to produce more pollen (Choi et al., 2021). These environmental changes have health consequences. Pollen and mold exposure contribute to allergic rhinitis and asthma (Sapkota et al., 2019), with a limited number of studies identifying relationships with hospitalizations and mortality in people with underlying COPD (Idrose et al., 2022). A meta-analysis found that each exposure increase of 10 grass pollen grains per m^3 was associated with a 1.88% increase in asthma emergency department visits (95% CI [0.94, 2.82%]) (Erbas et al., 2018), while high grass and ragweed pollen concentrations were associated with chronic respiratory mortality in a Michigan study (Larson et al., 2025). Elevated fungal spores have also been linked to increased asthma medication use, symptom severity, and hospitalizations (D'Amato et al., 2020).

5.6 COMPOUNDING AND CASCADING EFFECTS

Understanding the compounding effects of climate change is important because multiple hazards—such as heat waves, drought, and wildfires—can occur simultaneously or sequentially in a single individual's life, amplifying both acute and chronic health risks (see Chapter 3, Section 3.7). Exposure to these compound events can increase morbidity and mortality above what would be expected from any individual event alone, due to synergistic stress on physical and mental health as well as health care infrastructure. For example, simultaneous exposure to heat and air pollution such as wildfire smoke can exacerbate respiratory and cardiovascular illness leading to increased hospitalizations for people with asthma (Anenberg et al., 2020; Chen et al., 2024; Jones-Ngo et al., 2025). At the same time, exposures to smoke and to extreme heat can aggravate psychological stress and other mental health outcomes (Eisenman and Galway, 2022; Nori-Sarma et al., 2022).

Beyond acute impacts, longitudinal studies underscore that repeated exposures to hazards including extreme weather events may have cumulative detrimental effects on long-term health outcomes, including increased risk for chronic diseases, mental health disorders, and early mortality (Leppold et al., 2022). Multiple exposures over a person's lifetime can heighten the biological wear and tear known as "allostatic load" and overwhelm coping mechanisms. In addition, multiple or consecutive extreme events experienced by a region can overwhelm health care resources. As a result, the intersecting and repeated challenges of climate change over years or decades pose a threat to health that exceeds the effects of isolated exposures.

6

Impacts on Public Welfare

6.1 KEY MESSAGES

Climate-driven changes in temperature and precipitation extremes and variability are leading to negative impacts on agricultural crops and livestock, even as technological and other changes have increased agricultural production. There is increasing evidence of effects of excess heat and precipitation extremes on crop yields in the southeast United States, of increasing drought conditions in western U.S. agriculture, and negative impacts on agricultural crops in the Midwest. Impacts of heat stress on livestock include increased susceptibility to disease and mortality, and reduced milk production and reproduction rates.

Climate change, including increases in climate variability and wildfires, is changing the composition of forests and affecting grassland ecosystems and the services they provide. Changes in temperature and precipitation also alter phenology, tree migration (range), and interactions with pests and pathogens. Drought and other climate conditions are increasing the risk of fire, and the increase in ozone production as temperatures warm, reduces crop yield and may reduce the chance of survival for some tree species.

Climate-related changes in water availability and quality vary across regions in the United States with some regions showing a decline. Drought affects the production of food which leads to supply shortages and increased prices. Reduced water quality in lakes and coastal waters has been linked to increased temperature, oxygen depletion in deeper waters, harmful algal blooms, and effects on freshwater and marine fisheries.

U.S. energy systems, infrastructure, and many communities are experiencing increasing stress and costs owing to the effects of climate change. Increased temperatures have reduced efficiency in energy generation and transmission, while U.S. energy demand continues to increase. Transport systems have multiple stresses from climate change. Communities in Arctic regions are facing multiple threats from permafrost thaw, sea level rise, and declines in sea ice extent. Sea level rise and extreme weather pose increasing threats to the nearly 40% of the U.S. population who live in coastal counties.

6.2 CONSIDERING THE EVIDENCE

Climate change influences public welfare in a multitude of ways that affect the places where we live, work, and recreate; the food we consume; the water we drink and rely on to support agriculture and energy production; and the air we breathe. This chapter focuses on climate change effects only on major environmental systems that affect public welfare and are addressed in EPA (2009a), including agriculture, forests, grasslands, freshwaters, coastal oceans, and the built environment (energy, infrastructure, and settlements). Aspects of climate change, notably temperature and precipitation, will manifest differently in different regions of the United States. Thus, an evaluation of the evidence of the changing climate's impacts on public welfare is most appropriate when it considers the regional, if not subregional, level.

This chapter does not cover all ecosystems or public welfare impacts. Choices on what to highlight were guided by the committee's overall focus on impacts with more direct attribution to climate conditions and more direct impacts on human health and well-being, as well as responses to a public Request for Information. Nonetheless, the committee recognizes that growing bodies of literature address many other areas relevant to well-being, such as recreation, sport, hunting/fishing, and cultural heritage. Likewise, there is growing literature related to climate change and economics (see Box 6.1). Some examples of economic impacts of climate change are included, although an exhaustive review of economic impacts was beyond the scope of this report.

Like the approach used in EPA (2009a), this chapter includes discussion of direct impacts of climate change but also considers some other key indirect effects on public welfare, to put climate change impacts in the broader context of observed changes in environmental systems. The most significant and well-documented climate change effects on public welfare and the changes in the evidence that have occurred since 2009 are discussed here, including a better understanding of regional variability. In addition to addressing public welfare topics broadly, a few cross-cutting topics where linkages to public health (discussed in Chapter 5) are strong are highlighted, including

BOX 6.1
Economic Impacts

Many of the effects on human health and welfare discussed in this report have associated economic impacts. A growing number of studies since 2009 have estimated the economic effects associated with climate impacts on a range of economic sectors. For example, a study that calculated the costs associated with lost agricultural productivity is described in this chapter. For individuals who have directly experienced a climate impact, these economic impacts may directly affect their earning potential, the value of property they own, or other factors that contribute to their financial stability. Significant progress has been made since 2009 in analyzing sector-specific and economy-wide impacts of climate change, though challenges remain in considering climate impacts in the context of other economic drivers, such as changes in demographics, technology, and policy (NASEM, 2024c).

Empirical evidence of economic impacts has been used to establish exposure-response functions, which relate sector-specific economic impacts to climate indicators. These exposure-response functions can then be used to estimate potential climate-related damages associated with different future climate scenarios. Studies in the literature using empirical data to establish exposure-response relationships have expanded greatly since 2009 (e.g., Carleton and Greenstone, 2022; Clarke et al., 2018; Cromar et al., 2022; Depsky et al., 2023; Diaz, 2016; Moore et al., 2017; Rode et al., 2021; Shindell et al., 2020). It is now possible to estimate future economy-wide damages by aggregating these empirical exposure-response relationships for individual sectors (EPA, 2023). This is a significant advance since 2009, when most economy-wide analyses used relationships between large-scale economic indicators (e.g., Gross Domestic Product) and average changes in climate indicators (NASEM, 2017a). An alternative approach that is also substantially advanced since 2009 uses improved empirical data to evaluate economy-wide damages associated with each unit of change in the mean or variability of surface temperature or precipitation (e.g., Kalkuhl and Wenz, 2020; Kotz et al., 2021, 2022; Waidelich et al., 2024). Both the aggregated and economy-wide approaches estimate significant costs associated with future climate change and, although they have large uncertainties, their ranges overlap, providing increased confidence in their results.

wildfire (discussed in Chapters 3 and 5), the nutritional status of food, harmful algal blooms, and toxic-laden sediments from exposed lake beds carried as dust.

6.3 DRIVERS OF ECOSYSTEM CHANGE

Ecosystems are complex, encompassing interactions among many biological communities with important linkages with the physical environment and public welfare (IPBES, 2019). Climate is a key controller of the structure and function of ecosystems. Climate change-driven shifts, particularly in temperature and precipitation, are affecting the range of services that ecosystems and the built environment provide. Linkages among temperature, precipitation, and other climate factors are explored throughout this chapter.

Generally, across the public welfare areas discussed in EPA (2009a), recent evidence has strengthened the 2009 conclusions. New evidence has also led to improved understanding of the complex interactions among climate and non-climate drivers that influence observed changes in ecosystems and the built environment, and public welfare they support. In particular, the understanding of the regional variability of impacts and the complexity of other factors (e.g., land use, air quality, pests, and pathogens) that interact with climate impacts has grown. Discussion of these interactions and variability are addressed in this chapter.

Elevated Carbon Dioxide Effects on Plant Growth

Increases in atmospheric carbon dioxide (CO_2) concentrations and a climate-driven lengthening of the growing season offer positive “carbon fertilization” effects on plant growth (Norby et al., 2005; Song et al., 2019). However, these beneficial impacts will not likely fully mitigate losses associated with climate factors including heat stress, increased water demand, decreased water or nitrogen availability, or enhanced transfer of carbon below ground as plants respond to the need for additional nitrogen (Long, 1991; Mason et al., 2022; Possinger et al., 2025; Wolfe et al., 1998). Carbon fertilization benefits have been difficult to detect in forests (Girardin et al., 2016; Possinger et al., 2025). Moreover, rapid growth does not necessarily translate to higher crop yields because faster development results in smaller plants, a shortened reproductive period, and reduced yield (Hatfield and Prueger, 2015; Hatfield et al., 2011; Zhu et al., 2021).

Other Effects of Greenhouse Gases on Plants

Methane (CH_4) emissions lead to increased ground-level ozone (see Chapter 3), which damages many crops and trees. For the United States, analysis by the United Nations Environment Programme provides estimates of crop yield losses driven by CH_4 emissions (via induced climate, ozone, and CO_2 changes), finding yield losses of roughly 1,750,000 metric tons of maize (corn), 340,000 metric tons of wheat, 60,000 metric tons of rice, and 790,000 metric tons of soybeans for every 100 million metric tons emitted (UNEP and CCAC, 2021).[1] For context, 100 million metric tons represents about 25% of current anthropogenic CH_4 emissions, and these losses represent 0.6–1.3% of global yields of these crops with values up to 3–4% for individual countries (UNEP and CCAC, 2021). Non-CO_2 greenhouse gases (GHGs), such as nitrous oxide (N_2O) or fluorinated gases, affect plants only via climate change.

Non-Climate Drivers

Important drivers of environmental system changes beyond those linked to climate can amplify or mitigate public welfare effects. These non-climate drivers include land use and land cover change, pests and pathogens, nitrogen deposition, and changes in air quality driven by air pollution emissions not mediated through climate change. These non-climate drivers occur coincidently with climate change but are highly variable in space and time. At the same time, some of these non-climate drivers are affected by climate change (e.g., ozone and nitro-

[1] These values were obtained from Tables 3.6a-d in UNEP and CCAC (2021) and scaled to report values per 100 million metric tons.

gen deposition, noted in Chapter 3) and have also been shown to either amplify or mitigate ecosystem response to a changing climate (e.g., Baron et al., 2013; Bytnerowicz et al., 2007). Non-climate drivers contributing to the impacts discussed are noted throughout relevant sections in this chapter.

6.4 FOOD PRODUCTION AND AGRICULTURE

Agriculture production and climate are intrinsically linked, and evidence collected since 2009 strengthens messages conveyed in EPA (2009a). In this section, the committee details major effects of climate and interacting non-climate drivers on crop production, agricultural pests and weeds, and livestock.

Climate Effects on Crop Production

Increases in temperatures and variability in precipitation amount and intensity have negatively affected agricultural production in the United States (Eck et al., 2020; Hatfield et al., 2011; Lesk et al., 2022), although the extent of this impact varies by region. For the period of 1991–2017, temperature-related crop losses have resulted in $27 billion in crop insurance claims (Diffenbaugh et al., 2021). Increased temperature has lengthened the frost-free days by 2 weeks since 1970;[2] however, a longer growing season increases the need for water and nutrients (fertilizer) to take advantage of the additional crop growth potential.

Winters are also warming, as documented by the U.S. Department of Agriculture Plant Hardiness Zone Map,[3] which provides guidance on where specific plants are most likely to thrive. The hardiness zones have been adjusted northward, most recently in both 2012 and 2023. These maps are developed using 30-year averages of the lowest annual winter temperature at given locations, reflecting a trend in temperatures with direct implications for plant growth.

Extreme heat, drought, and moisture excess are increasingly co-occurring within a single growing season since 2000, resulting in up to 30% yield losses globally, with the United States noted as a region of greatest losses (Lesk et al., 2022). Similarly, extreme heat events and warm nights have decreased yields, and episodic temperature increases that exceed plant physiologic thresholds reduce yield and cause plant stress throughout the life of the crop, especially during flowering (Hatfield et al., 2011; Schlenker and Roberts, 2009).

Variability in temperature and precipitation effects has been observed across U.S. regions. For example, excess heat and precipitation extremes within the growing season have negatively affected crop yield in the southeast United States (Eck et al., 2020). The western United States has become hotter and drier in recent years (1976–2019) with associated negative impacts on agriculture production and other ecosystems (Su et al., 2021; Zhang et al., 2021).

Increasing temperatures across the United States have increased evaporation and plant transpiration (water evaporation from the plant surface). This change leads to an increase in water deficits and crop economic losses (Hatfield et al., 2011). In some parts of the United States, water will become less available from both reductions in rainfall and increasing drawdown of water for irrigation (e.g., the Ogallala region in the Great Plains). Hot-dry-windy events have significantly increased in the U.S. Great Plains from 1982 to 2020. These events have resulted in a 4% yield reduction per 10 hours of hot-dry-windy conditions during the reproductive stage of wheat (Zhao et al., 2022).

In addition to direct effects of temperature and precipitation, changes in the nutritional value of crops have been observed when grown under elevated CO_2 conditions (see also Chapter 5 discussion). Non-legume crop species often have lower protein content when grown under elevated CO_2 (Kimball, 2010). C_3 (cool season) grains and legumes have lower concentrations of zinc and iron when grown under elevated $CO_{2,}$ while C_4 (warm season) crops are less affected (Dietterich et al., 2015; Myers et al., 2014). These nutritional changes affect dietary needs for both human food crops and livestock forage.

[2] See https://www.epa.gov/climate-indicators/climate-change-indicators-length-growing-season (accessed September 2, 2025).
[3] See https://planthardiness.ars.usda.gov (accessed September 8, 2025).

While many climate impacts have been observed, negative impacts might be more severe in the absence of efforts to adapt or improve agricultural practices in response to observed change. These adaptive measures include actions such as plant breeding, crop switching, soil management, and improved technologies (e.g., irrigation, water conservation, and precision agriculture).

Crop Pests and Weeds

Temperature is the single most important factor affecting insect ecology, epidemiology, the number of generations per growing season, and insect distribution (Skendžić et al., 2021). Warmer winters affect crops and weeds and also expand the potential habitable range of some insect and disease pests. Plant pathogens are highly responsive to humidity and rainfall, as well as temperature (Lahlali et al., 2024). Since 1960, data have documented a northward shift in pests (Bebber et al., 2013), and pests are expected to reduce crop yield as a result of warming (Deutsch et al., 2018). Increased pests may also result in more chemical applications at a cost to the farmer and the environment.

Many C_3 weed species show substantial growth increases and resistance to herbicides when grown at elevated CO_2 levels (Ziska, 2003; Ziska et al., 1999). As a result, rising atmospheric CO_2 could lead to yield reductions when weed control is insufficient, potentially increasing the need for chemical applications, increasing costs to farmers and chemicals in the environment.

Climate Effects on Livestock

The EPA (2009a) discussion of livestock production is supported with new evidence and strengthened by recent research findings. A growing body of evidence indicates that summer heat stress has negative impacts on animal behavior. Livestock performance depends on their environment. The direct effects of temperature, variable precipitation, and extreme events impact thermoregulation, metabolism, and immune system function (Cheng et al., 2022). Heat stress increases susceptibility of livestock to diseases and death and decreases weight gain, milk production, and reproduction rate. For instance, from 2012 to 2016, milk yield was shown to be reduced by 1% due to heat stress resulting in $253 million in lost revenue across 19 states (Hutchins et al., 2025). Another study found that in 2010, lower milk production due to heat stress resulted in up to $1.2 billion in losses to the dairy sector (Key et al., 2014).

In addition to hotter summer temperatures generally, animals are experiencing more extreme heat events and temperature swings, which also impact animal behavior and stress. This heat exposure is more acute for cattle on grazing lands because fewer options exist for mitigating heat effects. In addition, having cattle on grazing lands that are susceptible to fires brings the animals into close proximity to both fire and smoke.

Indirect effects of climate change on livestock relate to feed production (declines in and reduced nutritional value), changes in water availability linked to shifting precipitation patterns, and increased exposure to pests and parasites. In grazing systems, livestock production is reduced by lower forage quality due to higher temperature, elevated CO_2, and drought stress (Polley et al., 2013).

Climate Impacts on Commercial Fisheries

Climate change resulting from GHG emissions has impacted commercial marine fisheries in every coastal region of the United States. Impacts on fisheries include losses in the abundance and quality of harvested species and fisheries-related revenue and job loss (Fisher et al., 2021; Free et al., 2019; Pershing et al., 2018). Changes in climate are not the only drivers affecting fish populations but are additional stressors that can exacerbate other negative impacts and overwhelm and outpace even gold-standard fisheries' management regimes, such as the North Pacific Fishery Management Council and the National Oceanic and Atmospheric Administration Fisheries in the Gulf of Alaska. Although some marine species have benefitted from ocean warming, for example the northern stock of American lobster (Le Bris et al., 2018), a variety of climate conditions related to warming have produced declines in other species. For example, low sea ice conditions and a long period of warming temperatures in the Bering Sea led to declines in stocks of Pacific cod and snow crab (Fedewa et al., 2020; Spies et al., 2020).

Negative responses have been observed in marine fisheries' populations near the warmer edge of their range, though a history of overfishing and other ocean changes are also contributing factors (Free et al., 2019). Populations showing a positive response were those on the cold edge of the species range. USGCRP (2023) noted that the incidence of disaster declarations for commercial fisheries rose from 1994 to 2019, and the majority of those disasters (more than 84%) were linked to extreme environmental events.

6.5 FORESTS

Forests are a critical resource for the United States, covering approximately a third of the nation's land area. The forest products industry represents about 4.7% of total U.S. manufacturing gross domestic product and serves as an important manufacturing sector in the United States (AF&PA, 2022). Forest cover has decreased slightly in the contiguous United States over the last 20 years largely due to expansion of croplands and urbanization, which includes increases in development at the wildland–urban interface (USGCRP, 2023). Forests are dominated by trees and woody vegetation and are commonly situated in the headwaters of freshwater ecosystems (i.e., wetlands, rivers, streams, lakes). As a result, forest and freshwater ecosystems are often intimately connected, with the structure and function of each dependent on the processes and resources the other supplies.

Forests provide a suite of services including marketable forest products, cleansing the atmosphere of pollutants, retaining nutrients, influencing water supply, and flood and erosion control (USGCRP, 2023). Spending time in forests has also been shown to have positive health effects for people (Jimenez et al., 2021). Additionally, forests also serve to regulate climate by the net removal of CO_2 from the atmosphere through photosynthesis and storage in tree biomass and soils. Forests also provide rich biodiversity, aesthetics, recreation, and cultural experiences (USGCRP, 2023).

Climate Effects on Forests

Climate change, including increases in climate variability, is changing the community composition and function of forest ecosystems and the services they provide (Campbell et al., 2022). Often these changes are subtle, manifested over decades and difficult to detect without careful long-term observation (Jones and Driscoll, 2022). In contrast, extreme events such as intense storms, extreme heat or prolonged wet or dry conditions, increases in pests and pathogens, and fire can have more marked effects on forests than those observed under gradual change (Andrus et al., 2025; Smith, 2011; Ummenhofer and Meehl, 2017).

There are several mechanisms by which climate change affects forest ecosystems. Increases in temperature may either increase or decrease tree growth due to changes in soil nutrient availability, hydraulic conductivity, and vapor pressure deficit (Grossiord et al., 2020; McDowell et al., 2020). Increases in precipitation and humidity are expected to increase tree growth through decreases in water deficit stress and increases in weathering and nutrient availability. At the same time, decreases in precipitation correspondingly decrease tree growth, but it has been shown that extreme dry conditions decrease growth more than wet extremes increase growth (Dannenberg et al., 2019). Both changes in temperature and precipitation also alter phenology and tree migration (range).

Forest ecosystems also sequester and store carbon, thereby providing some mitigation of human-caused CO_2 emissions (Pan et al., 2011). Understanding of this benefit has been greatly strengthened since EPA (2009a). In the United States, forests are a large net carbon sink, meaning they remove much more carbon from the atmosphere than they release (USGCRP, 2023). However, the strength of the U.S. forest carbon sink has declined over recent decades, due in part to climate-related disturbances largely associated with wildfires and insect outbreaks, and in part to forest management and land use change associated with increases in urbanization and agriculture (USGCRP, 2023). Hogan et al. (2024) evaluated trends in forest productivity in the United States, finding generally positive trends in productivity in the eastern United States under mild warming and increases in precipitation. In contrast, forest productivity was found to decline in much of the West where warming was more pronounced and precipitation decreased.

The U.S. Department of Agriculture Forest Inventory and Analysis database is a critical tool for quantifying forest resources within the United States and understanding forest change. Recent analysis of changes in the growth and survival of tree species across the contiguous United States demonstrate mixed responses to climate drivers (Clark et al., 2024) with potential implications for the services forest provide. Growth of 44 of 153 tree species studied decreased with increases in mean annual temperature, whereas fewer than 20 species in either the eastern or western United States exhibited negative growth associations with trends in mean annual precipitation. Average annual growth and decadal survival generally decreased with wetter conditions in the East and drier conditions in the West. Only eight species considered were tolerant of increases in temperature. In the East, 24 species were found to be tolerant of increases in precipitation and only seven in the West were tolerant of decreases in precipitation. There were at least a few species that had a similar response (either positive or negative) across the contiguous United States for growth and survival metrics.

The Forest Inventory and Analysis database has also recently been used to evaluate ozone impacts on forest growth and survival of 88 tree species in the contiguous United States (Pavlovic et al., 2025). As a whole, ozone exposure was generally below critical levels to impair tree growth, but exceeded levels needed to protect survival for some species.

As discussed in Chapter 3 of this report, wildland fires are a growing climate concern for forested ecosystems. At present the public health risks associated with these fires (discussed in Chapter 5 of this report) are a dominant impact on public welfare, though other effects such as increased homeowners' insurance premiums in fire-prone areas are growing.

Forest Pests and Pathogens

As with crops, pests and pathogens are an important driver of tree growth and mortality and fungal composition and function, whose impacts have been markedly altered and intensified by a changing climate (Simler-Williamson et al., 2019). These impacts occur through tree physiology, mortality, and morbidity (Andrus et al., 2025; Cobb and Metz, 2017; Preston et al., 2016). Increases in pathogens and insect pests cause changes in forest composition (Metz et al., 2012), disrupt food webs (Ellison et al., 2005), and alter biogeochemical processes (Preston et al., 2016). Climate change alters the survival rates of pests and pathogens (Simler-Williamson et al., 2019). Often rates of over-winter survival limit outbreaks, but increasing winter temperatures have been linked to increasing pest occurrence and impacts (McAvoy et al., 2017). Moreover, changes in temperature, humidity, and precipitation affect the reproduction and growth rates of pests and pathogens. In addition to effects on pests and pathogens, climate change can also impact the susceptibility of a tree host to infection, invasion, or damage resulting in changes in physiology, morphology, and population or community structure.

6.6 GRASSLANDS

Grasslands account for approximately 29% of U.S. land area and serve as an important ecosystem for livestock grazing and supporting wildlife. Grasslands are an important ecosystem for carbon storage; globally, more than 30% of terrestrial carbon occurs in grasslands soils (Bai and Cotrufo, 2022). Grasslands in the Great Plains were estimated to contain 34.9% of the total carbon stocks in the region from 2001 to 2005 (Pendall et al., 2018). It has been estimated that U.S. grazing lands contribute 14.7% of the U.S. soil carbon sequestration potential (Lal et al., 2003). Thus, grasslands are important for the economy and ecosystem services.

Increasing temperature can reduce grass productivity in tallgrass prairie (Koerner et al., 2023). Since 1984, the amount of plant biomass (known as annual net primary productivity) has increased in Great Plains grasslands due to increased growing season precipitation (Reeves et al., 2021). However, there are regional differences. The northern Great Plains may benefit from a longer growing season while the southwestern Great Plains will likely show a decline due to increased drought, higher temperature, and greater variability (McCollum et al., 2017). Since 2000, below average precipitation and above average temperature have been observed in the southwestern United States, indicative of a changing climate (Williams et al., 2023). This has reduced grassland productivity, with implications for grazing livestock production. Rangeland grazing capacity in New Mexico has declined by

43% over a 52-year period (1967–2018) due to higher growing season temperatures and increased frequency of drought (McIntosh et al., 2019).

Fire is a part of grassland ecology and historically has helped to suppress woody plants. However, a combination of elevated CO_2, increasing temperatures, and land and fire management practices is contributing to the expansion of trees into grasslands (Morford et al., 2022) resulting in a loss of livestock productivity.

6.7 COASTAL OCEAN ECOSYSTEMS

Coastal ocean ecosystems are experiencing warmer waters, sea level rise, increasing pressures from human development, and other stressors (May et al., 2023). These ecosystems play an important role in protecting coastlines. Tidal wetlands, which include mangroves and salt marshes, provide crucial habitats for fish and wildlife, and their dense vegetation helps to slow and absorb floodwaters, protecting inland areas from storm surges and high tides. Wetlands serve as important nursery grounds and feeding areas for many commercial fish species.

Sea level rise and increasing coastal hazards associated with climate change can drive tidal wetland loss (Weis et al., 2021). Tidal wetlands can move landward to escape rising sea levels, a process called inland migration. This can occur if there is space and time for the wetland to move inland before it erodes or is submerged. The evidence of potential loss has grown since EPA (2009a). A net loss of tidal wetlands is expected throughout the United States, but the rate and extent of loss will vary significantly from place to place depending on local conditions and inland migration. For example, loss and migration of tidal wetlands linked to sea level rise has been observed in the Chesapeake Bay (Schieder et al., 2018), Florida (Raabe and Stumpf, 2016), and New Jersey (Weis et al., 2021). Along the Pacific Coast, tidal wetlands cannot migrate inland due to coastal development and steep topography, increasing the chances of net tidal wetland loss due to sea level rise.

6.8 WATER RESOURCES

The amount and quality of water available for use by humans has direct impacts on welfare in a variety of ways. Drought affects the production of food, which leads to supply shortages and increased prices. Increases in land area inundated by flood waters imply increases in losses of life and property. Deteriorating water quality limits human use of water for multiple purposes, including drinking water and recreation.

Impacts of climate change on water resources, including water quality and water availability, droughts, and floods, are affected by regional hydroclimatology. For example, despite increasing air temperatures everywhere in the United States, some regions, such as much of the East, are experiencing significant increases in total precipitation, while in other regions, including parts of the West, precipitation is decreasing. This section provides technical information about impacts and recent trends and discusses the regional variability observed. Additional discussion of climate impacts on precipitation and drought is provided in Chapter 3 of this report.

Water Quality

The quality of many streams and rivers across the contiguous United States is declining in response to climate change, with implications for drinking water and municipal use, energy, fisheries, and other uses of freshwater. Water quality is affected by land cover and land use, and by many direct (e.g., sewage disposal) and indirect (e.g., use of fertilizers) human influences, creating complexity in understanding climate and non-climate drivers of water quality change. A recent review of 965 case studies indicated that 56% of observed water quality issues were related to climate change due to increasing water temperatures and changes in low flow periods (van Vliet et al., 2023). Some substances, such as nutrients and pharmaceuticals, show mostly increasing trends in concentrations, whereas others, such as sediment, biochemical oxygen demand, and metals show a mixture of increasing and decreasing trends in concentrations (van Vliet et al., 2023). Lakes have also been impacted by increasing temperatures in multiple ways, including a strengthening and lengthening period of thermal stratification, enhanced depletion of dissolved oxygen in deeper waters, loss of habitat for cold-water fisheries, and other threats such as spread of invasive species and loss of biodiversity (Jane et al., 2021, 2024; Woolway et al., 2022).

Harmful Algal Blooms

A consequence of warming waters and enhanced stratification of lakes and coastal waters is an increase in harmful algal blooms (Lefebvre et al., 2025; Townhill et al., 2018; Trainer et al., 2020). Additional changes in environmental conditions, such as increases in nutrients, can stimulate growth and blooms of cyanobacteria, called harmful algal blooms (Chapra et al., 2017). Understanding and documentation of climate-driven impacts of harmful algal blooms have increased greatly since 2009. In freshwaters, cyanobacteria (also known as blue-green algae) occur naturally and are able to outcompete other types of algae under warm water conditions (Cottingham et al., 2021). Some species of cyanobacteria can release toxins when environmental conditions are favorable, and the cyanobacteria present can express genes that produce the toxins. These toxins can harm people and animals drinking or recreating in contaminated waters or inhaling air near affected water sources (Plaas and Paerl, 2021). Under extreme conditions, when drinking water sources are affected, closures or additional treatment of the water supply may be needed.

In coastal waters, dinoflagellates or diatoms are the most common algae causing harmful algal blooms (Anderson et al., 2021). In coastal waters, fish kills have been reported when water temperatures are much higher than normal and associated with harmful algal bloom events. Shellfish contamination has been documented, with toxins making shellfish unsafe to consume (e.g., Lefebvre et al., 2025; McCabe et al., 2016).

For recreational fresh and coastal waters, many states post advisories in response to the occurrence of harmful algal blooms, warning people against contact during recreational activities and the potential for respiratory distress. Advisories have been listed for fresh and marine waters across the United States, from Florida to Alaska. There has been a marked increase in the number of advisories during the warm water months and in the annual total number of advisories since compilation was initiated in 2015.[4] These increases likely reflect increases in harmful algal bloom events, increased awareness of the problem, and improvements in monitoring efforts. Economic losses linked to harmful algal bloom impacts on coastal fisheries and aquaculture in the United States have been estimated to be tens of millions of dollars (Anderson et al., 2021; Jin et al., 2020).

Water Supply and Availability

Impacts of climate change on water supply and availability are complicated by the impacts of non-climate factors, such as changes in water consumption. Overall water withdrawals for all uses in the contiguous United States reported for 2015 were the lowest since 1970 (Warziniack et al., 2022). The primary consumptive uses of water are for irrigation and thermoelectricity generation. Water withdrawals for irrigation have remained relatively constant for decades despite increases in acreage under irrigation, presumably because of increases in efficiency (Warziniack et al., 2022). Withdrawals for thermoelectric power plant cooling have declined, again because of technological improvements (Warziniack et al., 2022).

Hydroclimatic changes driven by atmospheric warming include changes in precipitation and evapotranspiration demand. These changes interact with the land surface through exchanges of energy and water. The consequences of these changes are reflected in spatial and temporal patterns of precipitation, evapotranspiration, and soil moisture (Herrera et al., 2023). Changes of hydroclimate across the contiguous United States have changed the size and timing of rainfall over the past several decades (Marvel et al., 2021).

Baseflow Drought

A meteorological drought is a period of low precipitation that has cascading effects. The lack of precipitation delivered to the soil surface is accompanied by increased evaporation demand, which leads to soil moisture drought. Additionally, reduced recharge to shallow groundwater leads to baseflow (i.e., streamflow and groundwater flow) drought. The discussion in this section refers to baseflow drought (see Chapter 3 for discussion of meteorological drought). EPA (2009a) did not report significant evidence of increases in drought due to climate change in the decades leading up to 2009. There is now some evidence for increasing drought severity in some areas of the United States.

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[4] See the EPA Tracking CyanoHAB website at https://storymaps.arcgis.com/stories/d4a87e6cdfd44d6ea7b97477969cb1dd (accessed September 3, 2025).

Historical data show that drought magnitude is increasing in some regions and decreasing in others. For the period 1981–2020, drought duration and deficit were studied using reference (i.e., largely unimpacted by significant land-use changes) watersheds and were found to have decreased in the north and east and increased in the Southwest and south-central United States (Hammond et al., 2022). Alonso-Vicario et al. (2025) included catchments that were impacted by agriculture and urbanization, but the broad pattern for droughts across the United States was similar.

The impact of climate change in many regions may be confounded by the impact of other human activities (Vicente-Serrano et al., 2022). Attribution of increasing drought trends to climate change is difficult because the areas where these trends are observed overlap with areas of increasing water demand and land cover change. In the U.S. Southwest, decreasing flows in the Colorado River have been attributed to increased evapotranspiration driven by climate warming (Milly and Dunne, 2020). The observed 9.3% flow decrease per degree Celsius of warming is likely to continue in the future although it may be partially offset by increases in precipitation (Milly and Dunne, 2020).

Lag times between precipitation decreases and baseflow decreases are typically months and the duration of baseflow droughts from months to years. Baseflow droughts in watersheds unimpacted by human water use increased over the period from 1982 to 2012 in the mild temperate zone (Lee and Ajami, 2023). This zone consists generally of the Southeast, the eastern portion of the southern Great Plains, and the West Coast. In watersheds impacted by groundwater withdrawals, links to climate change are indirect (e.g., through the increased use of groundwater for irrigation). Meteorological droughts are linked to groundwater level declines in broad areas of the United States (Singh et al., 2025).

Lake levels have mostly increased across Alaska and the northern tier of the contiguous United States and have decreased in the intermountain West and the Southeast over the past two decades (Feng et al., 2022). Decreased water levels in terminal lakes in the Great Basin have been partially due to climate change (Hall et al., 2023). Declines in water levels in these terminal lakes have direct implications for human welfare as portions of exposed lake beds result in wind-blown sediments that contain toxic metals (see Chapter 5 for discussion of health effects of these toxins) (NASEM, 2020).

Floods

Across North America, the magnitude of extreme precipitation at the continental scale and at broad regional scales has increased (see also Chapter 3 of this report) (Kirchmeier-Young and Zhang, 2020). Like other aspects of water resources, flooding is influenced by many factors beyond climate. River floods are affected by characteristics of the land and by both the amount and timing of precipitation. Because of this combination of factors, regional-scale flood-hazard changes are not necessarily directly linked to precipitation changes (Blöschl, 2022), and some regions report no clear signal of increases in riverine floods despite the increases in extreme precipitation (Kundzewicz and Pińskwar, 2022). A more nuanced analysis that separates areas of rain-induced flooding and areas of snowmelt-induced flooding indicates that the annual maximum flood is increasing across the former and decreasing across the latter (Zhang et al., 2022).

In the western United States, data from reference watersheds indicate a decrease in the magnitude and frequency of rain-on-snow flooding, an increase for convective storm flooding, and little change in floods caused by other mechanisms (Huang et al., 2022). Patterns of flood magnitude trends studied across the contiguous United States show land use and hydroclimate change to be equally important in determining the trends (Kemter et al., 2023). Seasonal changes in flood frequency are also quite heterogeneous spatially, but in general show more declining trends in spring and summer and more increasing trends in autumn and winter (Gu et al., 2025). Trends in baseflow in rivers have been linked to trends in annual floods in North America (Berghuijs and Slater, 2023). The complex interactions among climate and land variables that result in river flows indicate that attribution of observed changes in flood magnitudes and frequencies will be uncertain (Scussolini et al., 2024).

Annual maximum snowpack decreased significantly in the contiguous United States from 1982 to 2016, and the snow season shortened by about a month (Zeng et al., 2018). These changes in snowpack have important implications for soil moisture limitations during summer, wildfires (see Chapter 3), and water supplies.

USGCRP (2023) highlights that flood hazards have disproportionate impacts on communities across the country. Coastal communities, communities situated on rivers, and agricultural and fishing communities experience more flood hazards (Edmonds et al., 2020; Thiault et al., 2019).

6.9 ENERGY, INFRASTRUCTURE, AND SETTLEMENTS

This section provides examples of climate change impacts on the built environment and describes their links to public welfare. For energy, this includes discussion of energy production as well as changes in demand associated with climate change. Similar to other welfare impacts discussed, impacts can be wide-ranging and have considerable geographic variability. Where people live (e.g., coastal regions or in or near forested areas) affects their vulnerability to some climate change impacts, such as coastal erosion or wildfires, with attendant economic loss (Deilami et al., 2018).

Heating and Cooling Requirements

Climate warming is increasing the number of cooling degree days and reducing heating degree days[5] in the United States (EPA, 2024b). The result is significantly increased demand for air conditioning. Air conditioning can help people remain in a temperature range that is comfortable and safe (see Box 5.1). Heat waves can result in both increased deaths and illness, with elderly and low-income populations particularly vulnerable to increased heat in urban areas[6] (Qian and Liu, 2025). Urban areas can be especially vulnerable to heat waves. Where the albedo (proportion of incident light that is reflected versus absorbed by a surface) is low, incoming heat is absorbed by the built environment, creating Urban Heat Islands, but attribution to increased GHG is difficult to establish (Martilli et al., 2020). Chapter 5 of this report provides a more detailed discussion of temperature effects on public health and associated impacts.

Energy Production

Demand for electricity is continuing to increase as a result of population growth, higher incomes, electrification of transportation, and internet services and data centers. Cooling needs due to warmer temperatures also has a significant impact on electricity demand. The peak demand for U.S. electricity was set in late afternoon in July 2025 at 759,180 megawatts, representing a 2% increase from the previous summer peak in 2024 (EIA, 2025c). Increasing peaks require investment in new generating, transmission, and distribution capacity.

Climate change is also increasing the costs of generating power (Bartos and Chester, 2015). As noted in EPA (2009a), warmer waters make the cooling of power plants less efficient, thus more costly, and warmer temperatures make energy transmission less efficient. Extreme weather events coupled with sea level rise in coastal areas create energy supply disruptions that require resiliency investments. Hydroelectric power generation is susceptible to decreases due to droughts and decreased snowpacks.

Infrastructure and Settlements

Climate change is affecting numerous settlements, especially in coastal regions.[7] For example, in Alaska, observed increases in coastal and riverbank erosion are causing damage and growing risks to settlements in numerous communities (Huntington et al., 2023). Rapidly warming temperatures in the Arctic region are leading to increased erosion through interactions with permafrost thaw, sea level rise, declines in sea ice extent, the lengthening of open water period, and increased impacts of storms along coastlines (Gibbs et al., 2021; Irrgang et al., 2022; Jones et al., 2020). In extreme cases, abandonment or relocation of affected settlements is needed. Inland areas are also subject to permafrost thaw, which can cause ground subsidence and landslides, affecting

[5] Degree days are calculated using the assumption that when it is 65°F, neither heating or cooling is needed, then calculating the difference between the daily temperature mean and 65°F. If the temperature mean is above 65°F, then 65 is subtracted from the mean to calculate Cooling Degree Days. If the temperature mean is below 65°F, the mean is subtracted from 65 to calculate the Heating Degree Days. See https://www.weather.gov/key/climate_heat_cool (accessed September 3, 2025).

[6] See https://www.cdc.gov/heat-health/risk-factors/heat-and-older-adults-aged-65.html (accessed September 3, 2025).

[7] See https://oceanservice.noaa.gov/facts/population.html (accessed September 3, 2025).

settlements and infrastructure (Makopoulou et al., 2025). The Gulf Coast is also experiencing similar settlement stresses due to sea level rise, hurricanes, and erosion that can cause relocations of communities (NASEM, 2024b).

Nearly 40% of the U.S. population currently lives in coastal counties. Sea level rise (discussed in Chapter 3) coupled with extreme weather has direct impacts on coastal infrastructure and settlements, including flooding, erosion, wind damage, and saltwater incursion to water supplies and cropland. For example, saltwater incursion and the pressure of the water even when it is not moving may damage structural foundations (Abdelhafez et al., 2022).

Increased wildfire severity (discussed in Chapter 3) is impacting infrastructure and settlements. In the western United States, structural losses due to wildfires increased over 200% between the decades 1999–2009 and 2010–2020 (Higuera et al., 2023). Wildland–urban interfaces are growing as settlements expand spatially into fire-prone areas, posing significant risks to structures and human health (see Chapter 5) (NASEM, 2022). The cost of insurance is also rising while the ability to retain and obtain insurance is declining in areas with wildfire risks (Auer, 2024).

Climate change also affects U.S. highway infrastructure, where impacts are driven by temperature, precipitation, sea level rise, and hurricanes (see discussion of hurricanes in Chapter 3). Table 6.1 details highway impacts (TRB, 2014). Increased costs are already being observed from effects such as softening asphalt due to high temperatures (Sias et al., 2025). Thermal expansion on roadways and bridges is also a significant issue (Zhiyuan et al., 2025). Other infrastructure systems experience similar impacts, including energy, public transportation, railroads, ports, military facilities, and water infrastructure.

TABLE 6.1 Summary of Climate Change Impacts on the Highway System

Climatic/Weather Change	Impact to Infrastructure	Impact to Operations/Maintenance
	Temperature	
Change in extreme maximum temperature	• Premature deterioration of infrastructure. Damage to roads from buckling and rutting. • Bridges subject to extra stresses through thermal expansion and increased movement.	• Safety concerns for highway workers limiting construction activities. • Thermal expansion of bridge joints, adversely affecting bridge operations and increasing maintenance costs. • Vehicle overheating and increased risk of tire blowouts. • Rising transportation costs (increased need for refrigeration). • Materials and load restrictions can limit transportation operations. • Closure of roads because of increased wildfires.
Change in range of maximum and minimum temperature	• Shorter snow and ice season. • Reduced frost heave and road damage. Later freeze and earlier thaw of structures because of shorter freeze-season lengths. Increased freeze–thaw conditions in selected locations creating frost heaves and potholes on road and bridge surfaces. • Increased slope instability, landslides, and shoreline erosion from permafrost thawing leads to damaging roads and bridges due to foundation settlement (bridges and large culverts are particularly sensitive to movement caused by thawing permafrost). • Hotter summers in Alaska lead to increased glacial melting and longer periods of high stream flows, causing both increased sediment in rivers and scouring of bridge supporting piers and abutments.	• Decrease in frozen precipitation would improve mobility and safety of travel through reduced winter hazards, reduce snow and ice removal costs, decrease need for winter road maintenance, and result in less pollution from road salt, and decrease corrosion of infrastructure and vehicles. • Longer road construction season in colder locations. • Vehicle load restrictions in place on roads to minimize structural damage due to subsidence and the loss of bearing capacity during spring thaw period (restrictions likely to expand in areas with shorter winters but longer thaw seasons). • Roadways built on permafrost likely to be damaged due to lateral spreading and settlement of road embankments. • Shorter season for ice roads.

continued

TABLE 6.1 Continued

Climatic/Weather Change	Impact to Infrastructure	Impact to Operations/Maintenance
	Precipitation	
Greater changes in precipitation levels	• If more precipitation falls as rain rather than snow in winter and spring, there will be an increased risk of landslides, slope failures, and floods from the runoff, causing road washouts and closures as well as the need for road repair and reconstruction. • Increasing precipitation could lead to soil moisture levels becoming too high (structural integrity of roads, bridges, and tunnels could be compromised leading to accelerated deterioration). • Less rain available to dilute surface salt may cause steel reinforcing in concrete structures to corrode. • Road embankments could be at risk of subsidence/heave. • Subsurface soils may shrink because of drought.	• Regions with more precipitation could see increased weather-related accidents, delays, and traffic disruptions (loss of life and property, increased safety risks, increased risks of hazardous cargo accidents). • Roadways and underground tunnels could close due to flooding and mudslides in areas deforested by wildfires. • Increased wildfires during droughts could threaten roads directly or cause road closures due to fire threat or reduced visibility. • Clay subsurfaces for pavement could expand or contract in prolonged precipitation or drought, causing pavement heave or cracking.
Increased intense precipitation, other change in storm intensity (except hurricanes)	• Heavy winter rain with accompanying mudslides can damage roads (washouts and undercutting), which could lead to permanent road closures. • Heavy precipitation and increased runoff can cause damage to tunnels, culverts, roads in or near flood zones, and coastal highways. • Bridges are more prone to extreme wind events and scouring from higher stream runoff. • Bridges, signs, overhead cables, and tall structures could be at risk from increased wind speeds.	• The number of road closures due to flooding and washouts will likely rise. • Erosion will occur at road construction project sites as heavy rain events take place more frequently. • Road construction activities could be disrupted. • Increases in weather-related highway accidents, delays, and traffic disruptions are likely. • Increases in landslides, closures or major disruptions of roads, emergency evacuations, and travel delays are likely. • Increased wind speeds could result in loss of visibility from drifting snow, loss of vehicle stability/maneuverability, lane obstruction (debris), and treatment chemical dispersion. • Lightning/electrical disturbance could disrupt transportation electronic infrastructure and signaling, pose risk to personnel, and delay maintenance activity.
	Sea Level	
Sea level rise	• Erosion of coastal road base and undermining of bridge supports due to higher sea levels and storm surges. Temporary and permanent flooding of roads and tunnels due to rising sea levels. • Encroachment of saltwater leading to accelerated degradation of tunnels (reduced life expectancy, increased maintenance costs and potential for structural failure during extreme events). • Further coastal erosion due to the loss of coastal wetlands and barrier islands, removing natural protection from wave action.	• Coastal road flooding and damage resulting from sea level rise and storm surge. • Increased exposure to storm surges. • More frequent and severe flooding of underground tunnels and other low-lying infrastructure.

TABLE 6.1 Continued

Climatic/Weather Change	Impact to Infrastructure	Impact to Operations/Maintenance
	Hurricanes	
Increased hurricane intensity	• Increased infrastructure damage and failure (highway and bridge decks being displaced).	• More frequent flooding of coastal roads. • More transportation interruptions (storm debris on roads can damage infrastructure and interrupt travel and shipments of goods). • More coastal evacuations.

SOURCE: TRB, 2014. Table formatting has been modified.

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Appendix A

Committee Member Biographies

Shirley Tilghman (NAS/NAM) (*Chair*) is a professor of molecular biology and public affairs emerita at Princeton University, where she served as the 19th president from 2001 to 2013. Following her retirement from the presidency, she returned to the faculty, where she had been teaching and conducting research since 1986 as an investigator of the Howard Hughes Medical Institute. Tilghman is best known for her pioneering work on genomic imprinting. She is a recipient of the L'Oréal-UNESCO Award for Women in Science, the Lifetime Achievement Award from the Society for Developmental Biology, the Genetics Society of America Medal for outstanding contributions to her field, and the society's George W. Beadle Award for contribution to the genetics community. Tilghman is a member of the National Academy of Sciences, the National Academy of Medicine, the American Philosophical Society, the Royal Society of London, and is an officer of the Order of Canada. She serves as a trustee of the Broad Institute of the Massachusetts Institute of Technology and Harvard University, the Institute for Advanced Study, the Simons Foundation and the Hypothesis Fund. Tilghman received an Honors B.Sc. in chemistry from Queen's University at Kingston, Canada, and a Ph.D. in biochemistry from Temple University. She previously served on the National Academies' Committee on Mapping and Sequencing the Human Genome, the Board on Life Sciences, and the Roundtable on Aligning Incentives for Open Science.

David T. Allen (NAE) is the Norbert Dittrich-Welch chair in chemical engineering and the codirector of the Center for Energy and Environmental Systems Analyses at the University of Texas at Austin. His expertise is in urban air quality and the engineering of sustainable systems. Allen has been a lead investigator for multiple air quality measurement and modeling studies, including studies that reported some of the first measurements of methane emissions from oil and gas supply chains. He is a member of the National Academy of Engineering and a recipient of the ENI Energy Transition Award. Allen previously served on the U.S. Environmental Protection Agency Science Advisory Board (EPA SAB) and the U.S. Department of Energy National Petroleum Council. He received a B.S. degree in chemical engineering with distinction from Cornell University, and an M.S. and Ph.D. in chemical engineering from the California Institute of Technology. Allen previously served on the National Academies' Committee on Anthropogenic Methane Emissions in the United States, the Board on Energy and Environmental Systems, and chaired the Committee on the Chemistry of Urban Wildfires.

Allen has previously provided consulting services to oil and gas companies and consortia involving oil and gas companies. The Center for Energy and Environmental Systems Analyses is supported by research gifts through an

Industrial Affiliates Program. During his service on the EPA SAB he co-authored public reports and made public statements related to methane emission regulations under consideration by the EPA.

Susan Anenberg is a professor and chair of the Environmental and Occupational Health Department at the George Washington (GW) University Milken Institute School of Public Health. She is also the director of the GW Climate and Health Institute. Previously, she was a cofounder and partner at Environmental Health Analytics, LLC, the Deputy Managing Director for Recommendations at the U.S. Chemical Safety Board, an environmental scientist at the U.S. Environmental Protection Agency (EPA), and a senior advisor for clean cookstove initiatives at the U.S. State Department. Anenberg's research focuses on the health implications of air pollution and climate change, from local to global scales. She currently serves on the World Health Organization's Global Air Pollution and Health Technical Advisory Group and previously served on the EPA Science Advisory Board and as president of the GeoHealth section of the American Geophysical Union. Anenberg received a B.A. in biology and environmental science from Northwestern University and a Ph.D. in environmental science and engineering and environmental policy from the University of North Carolina. She previously served on the National Academies' Committee on Utilizing Advanced Environmental Health and Geospatial Data and Technologies to Inform Community Investment and the Committee to Advise the U.S. Global Change Research Program.

Anenberg has previously submitted public comments on proposed EPA rules related to greenhouse gas emissions and air pollution. She receives research support for work on climate and health from the Natural Resources Defense Council. Annenberg signed a brief of amici curiae submitted to the Supreme Court in *State of West Virginia, et al., v. U.S. Environmental Protection Agency, et al*., that argued anthropogenic climate change, fueled by emissions of greenhouse gases such as carbon dioxide, harms public health in the United States.

Michele Barry (NAM) is the Drs. Ben & A. Jess Shenson professor of medicine and tropical diseases at Stanford University. She is also the director of the Center for Innovation in Global Health and senior associate dean for global health. Prior to her current role, Barry was a professor of medicine at Yale from which she was recruited to be the inaugural dean for global health at Stanford. She has published in the areas of climate's impact on health, tropical diseases, and human and planetary health. Barry is a member of the National Academy of Medicine (NAM), the Council on Foreign Relations, and the American Academy of Arts and Sciences. She is chair emerita of the board of directors for the Consortium of Universities for Global Health and a past president of the American Society of Tropical Medicine and Hygiene (ASTMH). Barry is a recipient of the Ben Kean Medal from the ASTMH and the Elizabeth Blackburn Award from the American Medical Woman's Association. She received an A.B. from Bryn Mawr College and an M.D. from the Albert Einstein College of Medicine. Barry previously served on the National Academies' Board on Global Health and has co-led the NAM climate interest group.

Charles T. Driscoll (NAE) is distinguished and university professor of environmental systems engineering in the Department of Civil and Environmental Engineering at Syracuse University, where he also serves as the director of the Center for Environmental Systems Engineering. His teaching and research interests are in environmental chemistry, biogeochemistry, and environmental quality modeling. A principal research focus has been the response of forest, aquatic, and coastal ecosystems to disturbance, including air pollution, climate and land use change, and elevated inputs of nutrients and mercury. Driscoll is a member of the National Academy of Engineering, a fellow of the American Association for the Advancement of Science and the 2023 Clarke Laurate in Water Science and Technology. He received his B.S. in civil engineering from the University of Maine and his M.S. and Ph.D. in environmental engineering from Cornell University. He previously served on the National Academies' Committee on Assessing Causality from a Multidisciplinary Evidence Base for National Ambient Air Quality Standards and the Board on Environmental Studies and Toxicology.

Driscoll currently serves in a compensated role on the advisory committee for The Penobscot Estuary Mercury Remediation Trusts for the Natural Resources Defense Council. Driscoll signed briefs of amici curiae submitted to the U.S. Court of Appeals District of Columbia Circuit in *American Lung Association, et al., v. U.S. Environmental Protection Agency, et al*., that argued that the Affordable Clean Energy Rule would cause an increase in carbon dioxide emissions and did not adequately consider impacts to historic resources and communities.

Susan Hanson (NAS) is an urban geographer, now retired for nearly 20 years from Clark University, where she taught for 25 years and was the Landry professor of geography and director of the School of Geography. Prior to Clark, she was an assistant and associate professor at the State University of New York (SUNY) Buffalo. Hanson's research has focused on the relationship between people and the urban built environment. This has included understanding people's everyday travel-activity patterns, examining the way that different groups make use of the city and showing how urban spatial structure configures household travel. She also seeks to understand the emergence of sustainable versus unsustainable practices in urban areas. Hanson's awards include the Lifetime Achievement Award and the Award for Creativity, both from the American Association of Geographers, as well as the Carey Award for Leadership & Service from the Transportation Research Board of the National Academies. She is a member of the American Academy of Arts and Sciences and the National Academy of Sciences. Hanson received an A.B. in geography from Middlebury College and an M.S. and Ph.D. in geography from Northwestern University. Prior to graduate school, she was a Peace Corps Volunteer in Western Kenya, teaching at a boys' secondary school.

Chris T. Hendrickson (NAE) is the Hamerschlag University professor of engineering emeritus and director of the Traffic 21 Institute at Carnegie Mellon University. His expertise is in engineering planning and management, including transportation systems, design for the environment, system performance, construction project management, finance, and computer applications. Central themes in his work are a systems-wide perspective and a balance of engineering and management considerations. Hendrickson is the editor-in-chief of the American Society of Civil Engineers (ASCE) *Journal of Transportation Engineering Part A (Systems)*. He is a recipient of the Council of University Transportation Centers Lifetime Achievement Award, the American Road & Transportation Builders Association Steinburg Award, the Faculty Award of the Carnegie Mellon Alumni Association, the Turner Lecture Award of the ASCE, and the Fenves Systems Research Award from the Institute of Complex Engineering Systems. Hendrickson is a member of the National Academy of Engineering, the National Academy of Construction, a fellow of the American Association for the Advancement of Science, and a distinguished member of the ASCE. Hendrickson received a B.S. in general engineering (resources strategy) and an M.S. in civil engineering from Stanford University, an M.Phil. in economics from Oxford University, and a Ph.D. in civil engineering from the Massachusetts Institute of Technology. He previously served on the National Academies' Committee on Accelerating Decarbonization in the United States: Technology, Policy, and Societal Dimensions and chaired the Transportation Research Board Division Committee.

Marika Holland is a senior scientist at the National Science Foundation National Center for Atmospheric Research (NSF NCAR). Her research is focused on polar climate variability and change. Holland has extensive experience in using climate models to study coupled climate interactions and has been active in the development of improved sea ice models for climate simulations. She has served as co-chair for the Polar Climate Working Group of the Community Earth System Model and chief scientist for the Community Earth System Model project. Holland contributed to the third, fourth, fifth, and sixth assessment reports of the Intergovernmental Panel on Climate Change. She is a fellow of the American Geophysical Union and the American Meteorological Society and a recipient of the International Arctic Science Committee Medal and the Community Earth System Model Distinguished Achievement Award. Holland received a Ph.D. in atmosphere and ocean sciences from the University of Colorado and was a postdoctoral fellow at the University of Victoria in British Columbia. She previously served on the National Academies' Committee on Understanding and Monitoring Abrupt Climate Change.

George M. Hornberger (NAE) is university professor emeritus at Vanderbilt University. He was previously the director of the Vanderbilt Institute for Energy and the Environment. Hornberger's work has focused on coupled natural-human systems and aimed to understand how climate, groundwater, surface water, energy production, food production, and human abstraction of water interact in complex ways. Hornberger is a fellow of the American Geophysical Union (AGU), a fellow of the Geological Society of America, and a fellow of the Association for Women in Science. He is a recipient of the AGU Robert E. Horton Award, the U.S. Geological Survey John Wesley Powell Award, the AGU Excellence in Geophysical Education Award. Hornberger is a member of the National Academy of Engineering and the American Academy of Arts and Sciences. He received a B.S. in civil engineering and an M.S. in hydrology from Drexel University and a Ph.D. in hydrology from Stanford University. He previously served on the National Academies' Committee on Advancing a Systems Approach to Studying the Earth and the Water Science and Technology Board.

Arthur Lee retired from Chevron in 2024, where he was a Chevron fellow. During his Chevron career, he held roles of increasing responsibilities, including the corporation-wide formulation of strategic positioning and policy development on issues ranging from Chevron's internal energy policy to U.S. air pollution issues and actions addressing climate change concerns. He continues to mentor employees as Chevron fellow emeritus in retirement. Lee represented Chevron in numerous roles: chair of the International Petroleum Industry Environmental Conservation Association's Climate Change Working Group, member of the board of directors of the International Emissions Trading Association, and member of the executive committee of the International Energy Agency Greenhouse Gas R&D Programme. Prior to Chevron, Lee held positions as an engineer with the U.S. Environmental Protection Agency, Fluor Daniel Inc., and Directed Technologies. He served on the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment as review editor in the *Special Report on Carbon Dioxide Capture* and Storage, contributing author on geothermal energy in the *Special Report on Renewable Energy*, and again as review editor in the Sixth Assessment, and he was awarded a certificate recognizing his contribution to the IPCC's Nobel Peace Prize. Additionally, Lee served on the National Climate Assessment Development and Advisory Committee and was a coordinating lead author of the climate change adaptation chapter. Lee received a B.S. in chemical engineering from the Massachusetts Institute of Technology and an M.S. in chemical engineering from the California Institute of Technology. He previously served on the National Academies' Board on Atmospheric Sciences and Climate.

Kari C. Nadeau (NAM) is the chair of the Department of Environmental Health and the John Rock professor of climate science and population studies at the Harvard T.H. Chan School of Public Health. She is also a professor of medicine at Harvard Medical School and works at the Beth Israel Deaconess Medical Center. Her expertise is in immunology, allergies and asthma, and climate change solutions, with a focus on understanding how environmental and epigenetic factors affect the risk of developing immune dysfunction. Her wet lab laboratory has been studying exposomics and solutions-facing research with policy-oriented outcomes. Nadeau has started four biotechnology companies, co-started a sustainability seed grant program, and works with the World Health Organization and United Nations on several projects in environmental and global health. She is a member of the National Academy of Medicine, the American Association of Physicians, the American Society of Clinical Investigation, and a fellow of the American Academy of Allergy, Asthma, and Immunology. Nadeau received a degree in biology from Haverford College and an M.D. and Ph.D. in biological chemistry and molecular pharmacology from Harvard Medical School. She completed a residency in pediatrics and a fellowship in allergy, asthma, and immunology.

Nadeau has previously submitted a public comment on proposed EPA rules related to greenhouse gas emissions and air pollution. She signed a brief of amici curiae submitted to the U.S. Court of Appeals Central District of California in *G.B., et al., v. U.S. Environmental Protection Agency, et al.*, that argued that children are uniquely vulnerable to the consequences of rising temperatures and to increased air pollution from climate change.

Charles W. Rice is a university distinguished professor in soil microbiology and holds the Vanier University professorship in the Department of Agronomy at Kansas State University. His research focuses on soil carbon and nitrogen, soil health, microbial ecology, and the impacts of climate change on agricultural and grassland ecosystems. Rice contributed to the third and fourth assessment reports of the Intergovernmental Panel on Climate Change (IPCC), and he was awarded a certificate recognizing his contribution to the IPCC's Nobel Peace Prize. Rice is a fellow of the Soil Science Society of America, the American Society of Agronomy, Sigma Xi, and the American Association for the Advancement of Science and a National Associate of the National Academies. He received a B.S. in natural environmental systems from Northern Illinois University and an M.S. in soil science and Ph.D. in soil microbiology from the University of Kentucky. He previously served on the National Academies' Board on Agriculture and Natural Resources.

Drew T. Shindell (NAS) is Nicholas professor of earth science at Duke University. He was previously a senior scientist at the National Aeronautics and Space Administration's Goddard Institute for Space Studies. His expertise is in modeling the impact of emissions changes, and his work has investigated how the atmospheric chemical system has important effects on humans through pollutants such as smog or particulates through acid rain and through stratospheric ozone change, and how climate can be altered by greenhouse gases, solar variability, volcanic eruptions, aerosols, and ozone, and what impacts changes in climate and air quality may have on society. Shindell contributed to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change and the Fifth National Climate Assessment. He is a member of the National Academy of Sciences and is a fellow of the American Geophysical Union and the American Association for the Advancement of Science. Shindell received a B.A. in physics from the University of California, Berkeley, and a Ph.D. in physics from the State University of New York Stony Brook. He previously served on the National Academies' Committee on the Provisions in the Internal Revenue Code on Greenhouse Gas Emissions and the Committee on Assessment of Himalayan Glaciers: Climate Change, Water Resources, and Water Security.

Shindell has previously submitted a public comment on proposed EPA rules related to greenhouse gas emissions and air pollution. He has also provided congressional testimony on the relationship between climate and health as well as greenhouse gas emissions. Shindell signed briefs of amici curiae submitted to the U.S. Court of Appeals District of Columbia Circuit in *Competitive Enterprise Institute, et al., v. National Highway Traffic and Safety Administration, et al.*, that argued that the Safer Affordable Fuel Efficient Vehicles Rule would not adequately address fossil fuel emissions from vehicles as well as a brief of amici curiae submitted to the U.S. Court of Appeals District of Columbia Circuit in *American Lung Association, et al., v. U.S. Environmental Protection Agency, et al.*, that argued that the Affordable Clean Energy Rule did not adequately consider impacts to historic resources and communities.

Graeme L. Stephens (NAE) is the director of the Center for Climate Sciences at the Jet Propulsion Laboratory (JPL). He was previously distinguished university professor at Colorado State University. Stephens is the principal investigator of the National Aeronautics and Space Administration's (NASA's) CloudSat mission, and previously chaired the World Climate Research Program Global Energy and Water and EXchanges (GEWEX) project, which examines the topic of global water cycles and the global energy balance and the connections between. His research activities focus on atmospheric radiation including the application of remote sensing in climate research to understand the role of hydrological processes in climate change. Stephens is a member of the National Academy of Engineering and a fellow of the Royal Society, American Meteorological Society, American Geophysical Union (AGU), and American Association for the Advancement of Science. He is a recipient of the American Meteorological Society's Houghton and Jule Charney Awards and the AGU Jule Charney Lecturer. Stephens received a B.S. in physics and meteorology and a Ph.D. in meteorology from the University of Melbourne, Australia. He previously served on the National Academies' Committee on Earth Science and Applications from Space.

David W. Titley is president and founder of RV Weather, providing weather and routing services to the recreational vehicle community. Previously, he was professor of practice in meteorology and professor of international affairs at the Pennsylvania State University. Titley served as a naval officer for 32 years and rose to the rank of rear admiral. His career included duties as commander of the Naval Meteorology and Oceanography Command, as well as oceanographer and navigator of the Navy. While serving at the Pentagon, Titley initiated and led the U.S. Navy's Task Force on Climate Change. After retiring from the Navy, he served as the deputy undersecretary of commerce for operations, the chief operating officer position at the National Oceanic and Atmospheric Administration. Titley is an expert on climate, the arctic, and national security. He received an honorary doctorate degree from the University of Alaska Fairbanks and is a fellow of the American Meteorological Society. Titley received a B.S. in meteorology from Pennsylvania State University, an M.S. in meteorology and physical oceanography and Ph.D. in meteorology from the Naval Postgraduate School. He previously served on the National Academies' Board on Atmospheric Sciences and Climate.

John C. Wall (NAE) retired from Cummins, Inc. in 2015, where he was chief technology officer. He has over 45 years of industry experience in the development of low-emission internal combustion engines and fuels and working with regulatory agencies in the United States and worldwide to align engine and fuel technologies with future emissions policy with the objective of delivering products meeting both commercial and environmental expectations. During his time with Cummins, Wall was directly involved in the most critical technology programs for low emissions, powertrain efficiency, and alternative fuels, and he also led the growth of the Cummins technical organization from 1,000 engineers, mostly centered in the United States to more than 6,000 engineers globally. Prior to joining Cummins, he led diesel fuels research for Chevron, where his team was first to discover the important contribution of fuel sulfur to diesel particulate emissions, leading to the first low-sulfur fuel standards by the U.S. Environmental Protection Agency (EPA) in 1994. Wall is a member of the National Academy of Engineering and a Society of Automotive Engineers (SAE) Fellow. He received the SAE Horning and Colwell Awards for research in the area of diesel fuel effects on emissions, SAE Pischinger Powertrain Innovation Award, and ASME Honda Medal for significant contributions in the field of personal transportation, the California Air Resources Board Haagen-Smit Award, and EPA Zosel Award for career accomplishments in diesel emission control and has been recognized by the Health Effects Institute for technologic innovation and commitment to clean air. Wall received an S.B., S.M., and Sc.D. in mechanical engineering from the Massachusetts Institute of Technology. He currently serves on the National Academies' Board on Science, Technology, and Economic Policy and previously served on the Board on Energy and Environmental Systems.

Appendix B

Disclosure of Unavoidable Conflicts of Interest

The conflict of interest policy of the National Academies of Sciences, Engineering, and Medicine (http://www.nationalacademies.org/coi) prohibits the appointment of an individual to a committee authoring a Consensus Study Report if the individual has a conflict of interest that is relevant to the task to be performed. An exception to this prohibition is permitted if the National Academies determine that the conflict is unavoidable and the conflict is publicly disclosed. A determination of a conflict of interest for an individual is not an assessment of that individual's actual behavior or character or ability to act objectively despite the conflicting interest.

Arthur Lee: Disclosure of Unavoidable Conflict(s) of Interest

Arthur Lee has a conflict of interest in relation to his service on the Committee on Anthropogenic Greenhouse Gases and the U.S. Climate: Evidence and Impacts because he holds stock in Chevron Corporation and has received reimbursement for travel expenses from Chevron incurred while mentoring employees in his capacity as Chevron Fellow Emeritus.

The National Academies have concluded that for this committee to accomplish the tasks for which it was established, its membership must include someone who has recent experience within the oil and gas sector, particularly in developing corporate internal energy policy on air pollution issues. As described in his biographical summary, Lee has extensive experience working at the intersection of climate change and energy production, with expertise in oil and gas infrastructure and evaluating the contributions of the oil and gas industry to climate change and strategies for reducing greenhouse gas emissions.

The National Academies have determined that the experience and expertise of Lee are needed for the committee to accomplish the task for which it has been established. The National Academies could not find another available individual with the equivalent experience and expertise who does not have a conflict of interest. Therefore, the National Academies have concluded that the conflict is unavoidable.

The National Academies believe that Lee can serve effectively as a member of the committee, and the committee can produce an objective report, taking into account the composition of the committee, the work to be performed, and the procedures to be followed in completing the study.

John Wall: Disclosure of Unavoidable Conflict(s) of Interest

Wall has a conflict of interest in relation to his service on the Committee on Anthropogenic Greenhouse Gases and the U.S. Climate: Evidence and Impacts because he owns stock in Cummins, Shell, and Chevron.

The National Academies have concluded that for this committee to accomplish the tasks for which it was established, its membership must include someone who has experience with the automotive industry focusing on developing emissions policy with the objective of delivering products meeting both commercial and environmental expectations. As described in his biographical summary, Wall has extensive experience working at the intersection of climate change and the automotive industry, with expertise in low-emission internal combustion engines and fuels and the environmental impacts of these emissions sources.

The National Academies have determined that the experience and expertise of Wall are needed for the committee to accomplish the task for which it has been established. The National Academies could not find another available individual with the equivalent experience and expertise who does not have a conflict of interest. Therefore, the National Academies have concluded that the conflict is unavoidable.

The National Academies believe that Wall can serve effectively as a member of the committee, and the committee can produce an objective report, taking into account the composition of the committee, the work to be performed, and the procedures to be followed in completing the study.

Appendix C

Executive Summary of the Technical Support Document for Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act (EPA, 2009a)

EXECUTIVE SUMMARY

This document provides technical support for the endangerment and cause or contribute analyses concerning greenhouse gas (GHG) emissions under section 202(a) of the Clean Air Act. This document itself does not convey any judgment or conclusion regarding the question of whether GHGs may be reasonably anticipated to endanger public health or welfare, as this decision is ultimately left to the judgment of the Administrator. The conclusions here and the information throughout this document are primarily drawn from the assessment reports of the Intergovernmental Panel on Climate Change (IPCC), the U.S. Climate Change Science Program (CCSP), the U.S. Global Change Research Program (USGCRP), and the National Research Council (NRC).

Observed Trends in Greenhouse Gas Emissions and Concentrations

Greenhouse gases, once emitted, can remain in the atmosphere for decades to centuries, meaning that 1) their concentrations become well-mixed throughout the global atmosphere regardless of emission origin, and 2) their effects on climate are long lasting. The primary long-lived GHGs directly emitted by human activities include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Greenhouse gases have a warming effect by trapping heat in the atmosphere that would otherwise escape to space.

In 2007, U.S. GHG emissions were 7,150 teragrams[1] of CO_2 equivalent[2] ($TgCO_2eq$). The dominant gas emitted is CO_2, mostly from fossil fuel combustion. Methane is the second largest component of U.S. emissions, followed by N_2O and the fluorinated gases (HFCs, PFCs, and SF_6). Electricity generation is the largest emitting sector (34% of total U.S. GHG emissions), followed by transportation (28%) and industry (19%).

[1] One teragram (Tg) = 1 million metric tons. 1 metric ton = 1,000 kilograms = 1.102 short tons = 2,205 pounds.

[2] Long-lived GHGs are compared and summed together on a CO2-equivalent basis by multiplying each gas by its global warming potential (GWP), as estimated by IPCC. In accordance with United Nations Framework Convention on Climate Change (UNFCCC) reporting procedures, the U.S. quantifies GHG emissions using the 100-year timeframe values for GWPs established in the IPCC Second Assessment Report.

Transportation sources under Section 202 of the Clean Air Act (passenger cars, light duty trucks, other trucks and buses, motorcycles, and cooling) emitted 1,649 $TgCO_2eq$ in 2007, representing 23% of total U.S. GHG emissions.

U.S. transportation sources under Section 202 made up 4.3% of total global GHG emissions in 2005, which, in addition to the United States as a whole, ranked only behind total GHG emissions from China, Russia, and India but ahead of Japan, Brazil, Germany, and the rest of the world's countries. In 2005, total U.S. GHG emissions were responsible for 18% of global emissions, ranking only behind China, which was responsible for 19% of global GHG emissions.

U.S. emissions of sulfur oxides (SOx), nitrogen oxides (NO_x), direct particulates, and ozone precursors have decreased in recent decades, due to regulatory actions and improvements in technology. Sulfur dioxide (SO_2) emissions in 2007 were 5.9 Tg of sulfur, primary fine particulate matter ($PM_{2.5}$) emissions in 2005 were 5.0 Tg, NO_x emissions in 2005 were 18.5 Tg, volatile organic compound (VOC) emissions in 2005 were 16.8 Tg, and ammonia emissions in 2005 were 3.7 Tg.

The global atmospheric CO_2 concentration has increased about 38% from pre-industrial levels to 2009, and almost all of the increase is due to anthropogenic emissions. The global atmospheric concentration of CH_4 has increased by 149% since pre-industrial levels (through 2007); and the N_2O concentration has increased by 23% (through 2007). The observed concentration increase in these gases can also be attributed primarily to anthropogenic emissions. The industrial fluorinated gases, HFCs, PFCs, and SF_6, have relatively low atmospheric concentrations but the total radiative forcing due to these gases is increasing rapidly; these gases are almost entirely anthropogenic in origin.

Historic data show that current atmospheric concentrations of the two most important directly emitted, long-lived GHGs (CO_2 and CH_4) are well above the natural range of atmospheric concentrations compared to at least the last 650,000 years. Atmospheric GHG concentrations have been increasing because anthropogenic emissions have been outpacing the rate at which GHGs are removed from the atmosphere by natural processes over timescales of decades to centuries.

Observed Effects Associated With Global Elevated Concentrations of GHGs

Current ambient air concentrations of CO_2 and other GHGs remain well below published exposure thresholds for any direct adverse health effects, such as respiratory or toxic effects.

The global average net effect of the increase in atmospheric GHG concentrations, plus other human activities (e.g., land-use change and aerosol emissions), on the global energy balance since 1750 has been one of warming. This total net heating effect, referred to as forcing, is estimated to be +1.6 (+0.6 to +2.4) watts per square meter (W/m^2), with much of the range surrounding this estimate due to uncertainties about the cooling and warming effects of aerosols. However, as aerosol forcing has more regional variability than the well-mixed, long-lived GHGs, the global average might not capture some regional effects. The combined radiative forcing due to the cumulative (i.e., 1750 to 2005) increase in atmospheric concentrations of CO_2, CH_4, and N_2O is estimated to be +2.30 (+2.07 to +2.53) W/m^2. The rate of increase in positive radiative forcing due to these three GHGs during the industrial era is very likely to have been unprecedented in more than 10,000 years.

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. Global mean surface temperatures have risen by 1.3 ± 0.32°F (0.74°C ± 0.18°C) over the last 100 years. Eight of the 10 warmest years on record have occurred since 2001. Global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries.

Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations. Climate model simulations suggest natural forcing alone (i.e., changes in solar irradiance) cannot explain the observed warming.

U.S. temperatures also warmed during the 20th and into the 21st century; temperatures are now approximately 1.3°F (0.7°C) warmer than at the start of the 20th century, with an increased rate of warming over the past 30 years. Both the IPCC and the CCSP reports attributed recent North American warming to elevated GHG concentrations. In the CCSP (2008g) report, the authors find that for North America, "more than half of this warming [for the period 1951–2006] is likely the result of human-caused greenhouse gas forcing of climate change."

Observations show that changes are occurring in the amount, intensity, frequency and type of precipitation. Over the contiguous United States, total annual precipitation increased by 6.1% from 1901 to 2008. It is likely that there have been increases in the number of heavy precipitation events within many land regions, even in those where there has been a reduction in total precipitation amount, consistent with a warming climate.

There is strong evidence that global sea level gradually rose in the 20th century and is currently rising at an increased rate. It is not clear whether the increasing rate of sea level rise is a reflection of short-term variability or an increase in the longer-term trend. Nearly all of the Atlantic Ocean shows sea level rise during the last 50 years with the rate of rise reaching a maximum (over 2 millimeters [mm] per year) in a band along the U.S. east coast running east-northeast.

Satellite data since 1979 show that annual average Arctic sea ice extent has shrunk by 4.1% per decade. The size and speed of recent Arctic summer sea ice loss is highly anomalous relative to the previous few thousands of years.

Widespread changes in extreme temperatures have been observed in the last 50 years across all world regions, including the United States. Cold days, cold nights, and frost have become less frequent, while hot days, hot nights, and heat waves have become more frequent.

Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases. However, directly attributing specific regional changes in climate to emissions of GHGs from human activities is difficult, especially for precipitation.

Ocean CO_2 uptake has lowered the average ocean pH (increased acidity) level by approximately 0.1 since 1750. Consequences for marine ecosystems can include reduced calcification by shell-forming organisms, and in the longer term, the dissolution of carbonate sediments.

Observations show that climate change is currently affecting U.S. physical and biological systems in significant ways. The consistency of these observed changes in physical and biological systems and the observed significant warming likely cannot be explained entirely due to natural variability or other confounding non-climate factors.

Projections of Future Climate Change With Continued Increases in Elevated GHG Concentrations

Most future scenarios that assume no explicit GHG mitigation actions (beyond those already enacted) project increasing global GHG emissions over the century, with climbing GHG concentrations. Carbon dioxide is expected to remain the dominant anthropogenic GHG over the course of the 21st century. The radiative forcing associated with the non-CO_2 GHGs is still significant and increasing over time.

Future warming over the course of the 21st century, even under scenarios of low-emission growth, is very likely to be greater than observed warming over the past century. According to climate model simulations summarized by the IPCC, through about 2030, the global warming rate is affected little by the choice of different future emissions scenarios. By the end of the 21st century, projected average global warming (compared to average temperature around 1990) varies significantly depending on the emission scenario and climate sensitivity assumptions, ranging from 3.2 to 7.2ºF (1.8 to 4.0ºC), with an uncertainty range of 2.0 to 11.5ºF (1.1 to 6.4ºC).

All of the United States is very likely to warm during this century, and most areas of the United States are expected to warm by more than the global average. The largest warming is projected to occur in winter over northern parts of Alaska. In western, central and eastern regions of North America the projected warming has less seasonal variation and is not as large, especially near the coast, consistent with less warming over the oceans.

It is very likely that heat waves will become more intense, more frequent, and longer lasting in a future warm climate, whereas cold episodes are projected to decrease significantly.

Increases in the amount of precipitation are very likely in higher latitudes, while decreases are likely in most subtropical latitudes and the southwestern United States, continuing observed patterns. The mid-continental area is expected to experience drying during summer, indicating a greater risk of drought.

Intensity of precipitation events is projected to increase in the United States and other regions of the world. More intense precipitation is expected to increase the risk of flooding and result in greater runoff and erosion that has the potential for adverse water quality effects.

It is likely that hurricanes will become more intense, with stronger peak winds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures. Frequency changes in hurricanes are currently too uncertain for confident projections.

By the end of the century, global average sea level is projected by IPCC to rise between 7.1 and 23 inches (18 and 59 centimeter [cm]), relative to around 1990, in the absence of increased dynamic ice sheet loss. Recent rapid changes at the edges of the Greenland and West Antarctic ice sheets show acceleration of flow and thinning. While an understanding of these ice sheet processes is incomplete, their inclusion in models would likely lead to increased sea level projections for the end of the 21st century.

Sea ice extent is projected to shrink in the Arctic under all IPCC emissions scenarios.

Projected Risks and Impacts Associated with Future Climate Change

Risk to society, ecosystems, and many natural Earth processes increase with increases in both the rate and magnitude of climate change. Climate warming may increase the possibility of large, abrupt regional or global climatic events (e.g., disintegration of the Greenland Ice Sheet or collapse of the West Antarctic Ice Sheet). The partial deglaciation of Greenland (and possibly West Antarctica) could be triggered by a sustained temperature increase of 2 to 7ºF (1 to 4ºC) above 1990 levels. Such warming would cause a 13 to 20 feet (4 to 6 meter) rise in sea level, which would occur over a time period of centuries to millennia.

CCSP reports that climate change has the potential to accentuate the disparities already evident in the American health care system, as many of the expected health effects are likely to fall disproportionately on the poor, the elderly, the disabled, and the uninsured. IPCC states with very high confidence that climate change impacts on human health in U.S. cities will be compounded by population growth and an aging population.

Severe heat waves are projected to intensify in magnitude and duration over the portions of the United

States where these events already occur, with potential increases in mortality and morbidity, especially among the elderly, young, and frail.

Some reduction in the risk of death related to extreme cold is expected. It is not clear whether reduced mortality from cold will be greater or less than increased heat-related mortality in the United States due to climate change.

Increases in regional ozone pollution relative to ozone levels without climate change are expected due to higher temperatures and weaker circulation in the United States and other world cities relative to air quality levels without climate change. Climate change is expected to increase regional ozone pollution, with associated risks in respiratory illnesses and premature death. In addition to human health effects, tropospheric ozone has significant adverse effects on crop yields, pasture and forest growth, and species composition. The directional effect of climate change on ambient particulate matter levels remains uncertain.

Within settlements experiencing climate change, certain parts of the population may be especially vulnerable; these include the poor, the elderly, those already in poor health, the disabled, those living alone, and/or indigenous populations dependent on one or a few resources. Thus, the potential impacts of climate change raise environmental justice issues.

CCSP concludes that, with increased CO_2 and temperature, the life cycle of grain and oilseed crops will likely progress more rapidly. But, as temperature rises, these crops will increasingly begin to experience failure, especially if climate variability increases and precipitation lessens or becomes more variable. Furthermore, the marketable yield of many horticultural crops (e.g., tomatoes, onions, fruits) is very likely to be more sensitive to climate change than grain and oilseed crops.

Higher temperatures will very likely reduce livestock production during the summer season in some areas, but these losses will very likely be partially offset by warmer temperatures during the winter season.

Cold-water fisheries will likely be negatively affected; warm-water fisheries will generally benefit; and the results for cool-water fisheries will be mixed, with gains in the northern and losses in the southern portions of ranges.

Climate change has very likely increased the size and number of forest fires, insect outbreaks, and tree mortality in the interior West, the Southwest, and Alaska, and will continue to do so. Over North America, forest growth and productivity have been observed to increase since the middle of the 20th century, in part due to observed climate change. Rising CO_2 will very likely increase photosynthesis for forests, but the increased photosynthesis will likely only increase wood production in young forests on fertile soils. The combined effects of expected increased temperature, CO_2, nitrogen deposition, ozone, and forest disturbance on soil processes and soil carbon storage remain unclear.

Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution. Sea level is rising along much of the U.S. coast, and the rate of change will very likely increase in the future, exacerbating the impacts of progressive inundation, storm-surge flooding, and shoreline erosion. Storm impacts are likely to be more severe, especially along the Gulf and Atlantic coasts. Salt marshes, other coastal habitats, and dependent species are threatened by sea level rise, fixed structures blocking landward migration, and changes in vegetation. Population growth and rising value of infrastructure in coastal areas increases vulnerability to climate variability and future climate change.

Climate change will likely further constrain already overallocated water resources in some regions of the United States, increasing competition among agricultural, municipal, industrial, and ecological uses. Although water management practices in the United States are generally advanced, particularly in the West, the reliance on past conditions as the basis for current and future planning may no longer be appropriate, as climate change increasingly creates conditions well outside of historical observations. Rising temperatures will diminish snowpack and increase evaporation, affecting seasonal availability of water. In the Great Lakes and major river systems, lower water levels are likely to exacerbate challenges relating to water quality, navigation, recreation, hydropower generation, water transfers, and binational relationships. Decreased water supply and lower water levels are likely to exacerbate challenges relating to aquatic navigation in the United States.

Higher water temperatures, increased precipitation intensity, and longer periods of low flows will exacerbate many forms of water pollution, potentially making attainment of water quality goals more difficult. As waters become warmer, the aquatic life they now support will be replaced by other species better adapted to warmer water. In the long term, warmer water and changing flow may result in deterioration of aquatic ecosystems.

Ocean acidification is projected to continue, resulting in the reduced biological production of marine calcifiers, including corals.

Climate change is likely to affect U.S. energy use and energy production and physical and institutional infrastructures. It will also likely interact with and possibly exacerbate ongoing environmental change and environmental pressures in settlements, particularly in Alaska where indigenous communities are facing major environmental and cultural impacts. The U.S. energy sector, which relies heavily on water for hydropower and cooling capacity, may be adversely impacted by changes to water supply and quality in reservoirs and other water bodies. Water infrastructure, including drinking water and wastewater treatment plants, and sewer and stormwater management systems, will be at greater risk of flooding, sea level rise and storm surge, low flows, and other factors that could impair performance.

Disturbances such as wildfires and insect outbreaks are increasing in the United States and are likely to intensify in a warmer future with warmer winters, drier soils, and longer growing seasons. Although recent climate trends have increased vegetation growth, continuing increases in disturbances are likely to limit carbon storage, facilitate invasive species, and disrupt ecosystem services.

Over the 21st century, changes in climate will cause species to shift north and to higher elevations and fundamentally rearrange U.S. ecosystems. Differential capacities for range shifts and constraints from development, habitat fragmentation, invasive species, and broken ecological connections will alter ecosystem structure, function, and services.

Climate change impacts will vary in nature and magnitude across different regions of the United States.

- Sustained high summer temperatures, heat waves, and declining air quality are projected in the **Northeast,**[3] **Southeast,**[4] **Southwest,**[5] and **Midwest.**[6] Projected climate change would continue to cause loss of sea ice, glacier retreat, permafrost thawing, and coastal erosion in **Alaska**.

[3] Northeast includes West Virginia, Maryland, Delaware, Pennsylvania, New Jersey, New York, Connecticut, Rhode Island, Massachusetts, Vermont, New Hampshire, and Maine.

[4] Southeast includes Kentucky, Virginia, Arkansas, Tennessee, North Carolina, South Carolina, southeast Texas, Louisiana, Mississippi, Alabama, Georgia, and Florida.

[5] Southwest includes California, Nevada, Utah, western Colorado, Arizona, New Mexico (except the extreme eastern section), and southwest Texas.

[6] The Midwest includes Minnesota, Wisconsin, Michigan, Iowa, Illinois, Indiana, Ohio, and Missouri.

- Reduced snowpack, earlier spring snowmelt, and increased likelihood of seasonal summer droughts are projected in the **Northeast, Northwest,**[7] and **Alaska.** More severe, sustained droughts and water scarcity are projected in the **Southeast, Great Plains,**[8] and **Southwest**.
- The **Southeast, Midwest,** and **Northwest** in particular are expected to be impacted by an increased frequency of heavy downpours and greater flood risk.
- Ecosystems of the **Southeast, Midwest, Great Plains, Southwest, Northwest,** and **Alaska** are expected to experience altered distribution of native species (including local extinctions), more frequent and intense wildfires, and an increase in insect pest outbreaks and invasive species.
- Sea level rise is expected to increase storm surge height and strength, flooding, erosion, and wetland loss along the coasts, particularly in the **Northeast, Southeast,** and **islands.**
- Warmer water temperatures and ocean acidification are expected to degrade important aquatic resources of **islands** and coasts such as coral reefs and fisheries.
- A longer growing season, low levels of warming, and fertilization effects of carbon dioxide may benefit certain crop species and forests, particularly in the **Northeast and Alaska.** Projected summer rainfall increases in the Pacific **islands** may augment limited freshwater supplies. Cold-related mortality is projected to decrease, especially in the **Southeast**. In the **Midwest** in particular, heating oil demand and snow-related traffic accidents are expected to decrease.

Climate change impacts in certain regions of the world may exacerbate problems that raise humanitarian, trade, and national security issues for the United States. The IPCC identifies the most vulnerable world regions as the Arctic, because of the effects of high rates of projected warming on natural systems; Africa, especially the sub-Saharan region, because of current low adaptive capacity as well as climate change; small islands, due to high exposure of population and infrastructure to risk of sea level rise and increased storm surge; and Asian mega-deltas, such as the Ganges-Brahmaputra and the Zhujiang, due to large populations and high exposure to sea level rise, storm surge and river flooding. Climate change has been described as a potential threat multiplier with regard to national security issues.

[7] The Northwest includes Washington, Idaho, western Montana, and Oregon.

[8] The Great Plains includes central and eastern Montana, North Dakota, South Dakota, Wyoming, Nebraska, eastern Colorado, Nebraska, Kansas, extreme eastern New Mexico, central Texas, and Oklahoma.