U.S. GLOBAL CHANGE RESEARCH PROGRAM
CLIMATE SCIENCE SPECIAL REPORT (CSSR)

Final Clearance
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EXECUTIVE SUMMARY

Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, B. DeAngelo, S. Doherty, K. Hayhoe, R. Horton, J.P. Kossin, P.C. Taylor, A.M. Waple, and C.P. Weaver, 2017: Executive summary. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 12-37.

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1. **Wuebbles**, D.J., D.R. Easterling, K. Hayhoe, T. Knutson, R.E. Kopp, J.P. Kossin, K.E. Kunkel, A.N. LeGrande, C. Mears, W.V. Sweet, P.C. Taylor, R.S. Vose, and M.F. Wehner, 2017: Our globally changing climate. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 38-97.
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APPENDICES

A. **Wuebbles**, D.J., 2017: Observational datasets used in climate studies. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 636-641.
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About This Report

As a key input into the Fourth National Climate Assessment (NCA4), the U.S. Global Change Research Program (USGCRP) oversaw the production of this special, stand-alone report of the state of science relating to climate change and its physical impacts.

This report is designed to be an authoritative assessment of the science of climate change, with a focus on the United States, to serve as the foundation for efforts to assess climate-related risks and inform decision-making about responses. In accordance with this purpose, it does not include an assessment of literature on climate change mitigation, adaptation, economic valuation, or societal responses, nor does it include policy recommendations.

The Climate Science Special Report (CSSR) serves several purposes for NCA4, including providing 1) an updated detailed analysis of the findings of how climate change is affecting weather and climate across the United States; 2) an executive summary that will be used as the basis for the science summary of NCA4; and 3) foundational information and projections for climate change, including extremes, to improve "end-to-end" consistency in sectoral, regional, and resilience analyses for NCA4. As an assessment and analysis of the science, this report provides important input to the development of NCA4 and its primary focus on the human welfare, societal, economic and environmental elements of climate change.

Much of this report is written at a level more appropriate for a scientific audience, though the Executive Summary is designed to be accessible to a broader audience.

Report Development, Review, and Approval Process

The National Oceanic and Atmospheric Administration (NOAA) served as the administrative lead agency for the preparation of this report. The Federal Science Steering Committee (SSC)[1] comprises representatives from four agencies (NOAA, the National Aeronautics and Space Administration [NASA], the Department of Energy [DOE], and the Environmental Protection Agency [EPA]), the U.S. Global Change Research Program (USGCRP),[2] and three Coordinating Lead Authors, all of whom were Federal employees during the development of this report. Following a public notice for author nominations in March 2016, the SSC selected the writing team, consisting of scientists representing Federal agencies, national laboratories, universities,

[1] The Science Steering Committee is a federal advisory committee that oversees the production of the CSSR.
[2] The USGCRP is made up of 13 Federal departments and agencies that carry out research and support the Nation's response to global change. The USGCRP is overseen by the Subcommittee on Global Change Research (SGCR) of the National Science and Technology Council's Committee on Environment, Natural Resources, and Sustainability (CENRS), which in turn is overseen by the White House Office of Science and Technology Policy (OSTP). The agencies within USGCRP are the Department of Agriculture, the Department of Commerce (NOAA), the Department of Defense, the Department of Energy, the Department of Health and Human Services, the Department of the Interior, the Department of State, the Department of Transportation, the Environmental Protection Agency, the National Aeronautics and Space Administration, the National Science Foundation, the Smithsonian Institution, and the U.S. Agency for International Development.

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and the private sector. Contributing Authors were requested to provide special input to the Lead Authors to help with specific issues of the assessment.

The first Lead Author Meeting was held in Washington, DC in April 2016, to refine the outline contained in the SSC-endorsed prospectus and to make writing assignments. Over the course of 16 months, 6 CSSR drafts were generated, with each successive iteration—from zero-order to fifth-order drafts—undergoing additional expert review, as follows: (i) by the writing team itself (13–20 June 2016); (ii) by the SSC convened to oversee report development (29 July–18 August 2016); (iii) by the technical agency representatives (and designees) comprising the Subcommittee on Global Change Research (SGCR, 3–14 October 2016); (iv) by the SSC and technical liaisons again (5–13 December 2016); (v) by the general public during the Public Comment Period (15 December 2016–3 February 2017) and an expert panel convened by the National Academies of Sciences (NAS, 21 December 2016–13 March 2017); and (vi) by the SGCR again (3–24 May 2017) to confirm the Review Editor conclusions that all public and NAS comments were adequately addressed. In October 2016, an 11-member core writing team was tasked with capturing the most important CSSR key findings and generating an Executive Summary. Two additional Lead Authors Meetings were held after major review milestones to facilitate chapter team deliberations and consistency: 2–4 November 2016 (Boulder, CO) and 21–22 April 2017 (Asheville, NC). Literature cutoff dates were enforced, with all cited material published by June 2017. The final (fifth-order) draft including the Executive Summary was compiled in June 2017, and submitted to the Office of Science and Technology Policy (OSTP). OSTP is responsible for the Federal clearance process prior to final report production and public release.

The Sustained National Climate Assessment

The Climate Science Special Report has been developed as part of the USGCRP's sustained National Climate Assessment (NCA) process. This process facilitates continuous and transparent participation of scientists and stakeholders across regions and sectors, enabling new information and insights to be assessed as they emerge. The Climate Science Special Report is aimed at a comprehensive assessment of the science underlying the changes occurring in Earth's climate system, with a special focus on the United States.

Sources Used in this Report

The findings in this report are based on a large body of scientific, peer-reviewed research, as well as a number of other publicly available sources, including well-established and carefully evaluated observational and modeling datasets. The team of authors carefully reviewed these sources to ensure a reliable assessment of the state of scientific understanding. Each source of information was determined to meet the four parts of the internal quality assurance guidance provided to authors (following the approach from NCA3): 1) utility, 2) transparency and traceability, 3) objectivity, and 4) integrity and security. Report authors assessed and synthesized

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information from peer-reviewed journal articles, technical reports produced by Federal agencies, scientific assessments (such as the rigorously-reviewed international assessments from the Intergovernmental Panel on Climate Change; IPCC 2013), reports of the National Academy of Sciences and its associated National Research Council, and various regional climate impact assessments, conference proceedings, and government statistics (such as population census and energy usage).

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Guide to the Report

The following subsections describe the format of the Climate Science Special Report and the overall structure and features of the chapters.

Executive Summary

The Executive Summary describes the major findings from the Climate Science Special Report. It summarizes the overall findings and includes some key figures and additional bullet points covering overarching and especially noteworthy conclusions. The Executive Summary and the majority of the Key Findings are written to be accessible to a wide range of audiences.

Chapters

Key Findings and Traceable Accounts

Each topical chapter includes Key Findings, which are based on the authors' expert judgment of the synthesis of the assessed literature. Each Key Finding includes a confidence statement and, as appropriate, framing of key scientific uncertainties, so as to better support assessment of climate-related risks. (See "Documenting Uncertainty" below).

Each Key Finding is also accompanied by a Traceable Account that documents the supporting evidence, process, and rationale the authors used in reaching these conclusions and provides additional information on sources of uncertainty through confidence and likelihood statements. The Traceable Accounts can be found at the end of each chapter.

Regional Analyses

Throughout the report, the regional analyses of climate changes for the United States are based on 10 different regions as shown in Figure 1. There are differences from the regions used in the Third National Climate Assessment (Melillo et al. 2014): 1) the Great Plains are split into the Northern Great Plains and Southern Great Plains; and 2) The U.S. islands in the Caribbean are analyzed as a separate region apart from the Southeast.

Chapter Text

Each chapter assesses the state of the science for a particular aspect of the changing climate. The first chapter gives a summary of the global changes occurring in the Earth's climate system. This is followed in Chapter 2 by a summary of the scientific basis for climate change. Chapter 3 gives an overview of the processes used in the detection and attribution of climate change and associated studies using those techniques. Chapter 4 then discusses the scenarios for greenhouse gases and particles and the modeling tools used to study future projections. Chapters 5 through 9 primarily focus on physical changes in climate occurring in the United States, including those projected to occur in the future. Chapter 10 provides a focus on land use change and associated

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feedbacks on climate. Chapter 11 addresses changes in Alaska in the Arctic, and how the latter affects the United States. Chapters 12 and 13 discuss key issues connected with sea level rise and ocean changes, including ocean acidification, and their potential effects on the United States. Finally, Chapters 14 and 15 discuss some important perspectives on how mitigation activities could affect future changes in climate and provide perspectives on what surprises could be in store for the changing climate beyond the analyses already covered in the rest of the assessment.

Throughout the report, results are presented in American units (e.g., degree Fahrenheit) as well as in the International System of Units (e.g., degrees Celsius).

Reference time periods for graphics

There are many different types of graphics in the Climate Science Special Report. Some of the graphs in this report illustrate historical changes and future trends in climate compared to some reference period, with the choice of this period determined by the purpose of the graph and the availability of data. The scientific community does not have a standard set of reference time periods for assessing the science, and these tend to be chosen differently for different reports and assessments. Some graphics are pulled from other studies using different time periods.

Where graphs were generated for this report (those not based largely on prior publications), they are mostly based on one of two reference periods. The 1901–1960 reference period is particularly used for graphs that illustrate past changes in climate conditions, whether in observations or in model simulations. This 60-year time period was also used for analyses in the Third National Climate Assessment (NCA3; Melillo et al. 2014). The beginning date was chosen because earlier historical observations are generally considered to be less reliable. Thus, a number of the graphs in the report are able to highlight the recent, more rapid changes relative to the early part of the century (the reference period) and also reveal how well the climate models simulate observed changes. In this report, this time period is used as the base period in most maps of observed trends and all time-varying, area-weighted averages that show both observed and projected quantities. For the observed trends, 1986–2015 is generally chosen as the most recent 30-year period (2016 data was not fully available until late in our development of the assessment).

The other commonly used reference period in this report is 1976–2005. The choice of a 30-year period is chosen to account for natural variations and to have a reasonable sampling in order to estimate likelihoods of trends in extremes. This period is consistent with the World Meteorological Organization's recommendation for climate statistics. This period is used for graphs that illustrate projected changes simulated by climate models. The purpose of these graphs is to show projected changes compared to a period that allows stakeholders and decision makers to base fundamental planning and decisions on average and extreme climate conditions in a non-stationary climate; thus, a recent available 30-year period was chosen (Arguez and Vose 2011). The year 2005 was chosen as an end date because the historical period simulated by the

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models used in this assessment ends in that year.

For future projections, 30-year periods are again used for consistency. Projections are centered around 2030, 2050, and 2085 with an interval of plus and minus 15 years (for example, results for 2030 cover the period 2015–2045); Most model runs used here only project out to 2100 for future scenarios, but where possible, results beyond 2100 are shown. Note that these time periods are different than those used in some of the graphics in NCA3. There are also exceptions for graphics that are based on existing publications.

For global results that may be dependent on findings from other assessments (such as those produced by the Intergovernmental Panel on Climate Change, or IPCC), and for other graphics that depend on specific published work, the use of other time periods was also allowed, but an attempt was made to keep them as similar to the selected periods as possible. For example, in the discussion of radiative forcing, the report uses the standard analyses from IPCC for the industrial era (1750 to 2011) (following IPCC 2013a). And, of course, the paleoclimatic discussion of past climates goes back much further in time.

Model Results: Past Trends and Projected Futures

The NCA3 included global modeling results from both the CMIP3 (Coupled Model Intercomparison Project, 3rd phase) models used in the 2007 international assessment (IPCC 2007) and the CMIP5 (Coupled Model Intercomparison Project, Phase 5) models used in the more recent international assessment (IPCC 2013a). Here, the primary resource for this assessment is the more recent global model results and associated downscaled products from CMIP5. The CMIP5 models and the associated downscaled products are discussed in Chapter 4: Projections.

Treatment of Uncertainties: Likelihoods, Confidence, and Risk Framing

Throughout this report's assessment of the scientific understanding of climate change, the authors have assessed to the fullest extent possible the state-of-the-art understanding of the science resulting from the information in the scientific literature to arrive at a series of findings referred to as Key Findings. The approach used to represent the extent of understanding represented in the Key Findings is done through two metrics:

- **Confidence** in the validity of a finding based on the type, amount, quality, strength, and consistency of evidence (such as mechanistic understanding, theory, data, models, and expert judgment); the skill, range, and consistency of model projections; and the degree of agreement within the body of literature.

- **Likelihood,** or probability of an effect or impact occurring, is based on measures of uncertainty expressed probabilistically (in other words, based on the degree of understanding or knowledge, e.g., resulting from evaluating statistical analyses of observations or model

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results or on expert judgment).

The terminology used in the report associated with these metrics is shown in Figure 2. This language is based on that used in NCA3 (Melillo et al. 2014), the IPCC's Fifth Assessment Report (IPCC 2013a), and most recently the USGCRP Climate and Health assessment (USGCRP 2016). Wherever used, the confidence and likelihood statements are italicized.

Assessments of confidence in the Key Findings are based on the expert judgment of the author team. Authors provide supporting evidence for each of the chapter's Key Findings in the Traceable Accounts. Confidence is expressed qualitatively and ranges from low confidence (inconclusive evidence or disagreement among experts) to very high confidence (strong evidence and high consensus) (see Figure 2). Confidence should not be interpreted probabilistically, as it is distinct from statistical likelihood. See chapter 1 in IPCC (2013a) for further discussion of this terminology.

In this report, likelihood is the chance of occurrence of an effect or impact based on measures of uncertainty expressed probabilistically (in other words, based on statistical analysis of observations or model results or on expert judgment). The authors used expert judgment based on the synthesis of the literature assessed to arrive at an estimation of the likelihood that a particular observed effect was related to human contributions to climate change or that a particular impact will occur within the range of possible outcomes. Model uncertainty is an important contributor to uncertainty in climate projections, and includes, but is not restricted to, the uncertainties introduced by errors in the model's representation of the physical and bio-geochemical processes affecting the climate system as well as in the model's response to external forcing (IPCC 2013a).

Where it is considered justified to report the likelihood of particular impacts within the range of possible outcomes, this report takes a plain-language approach to expressing the expert judgment of the chapter team, based on the best available evidence. For example, an outcome termed "likely" has at least a 66% chance of occurring (in other words, a likelihood greater than about 2 of 3 chances); an outcome termed "very likely," at least a 90% chance (or more than 9 out of 10 chances). See Figure 2 for a complete list of the likelihood terminology used in this report.

Traceable Accounts for each Key Finding 1) document the process and rationale the authors used in reaching the conclusions in their Key Finding, 2) provide additional information to readers about the quality of the information used, 3) allow traceability to resources and data, and 4) describe the level of likelihood and confidence in the Key Finding. Thus, the Traceable Accounts represent a synthesis of the chapter author team's judgment of the validity of findings, as determined through evaluation of evidence and agreement in the scientific literature. The Traceable Accounts also identify areas where data are limited or emerging. Each Traceable Account includes 1) a description of the evidence base, 2) major uncertainties, and 3) an assessment of confidence based on evidence.

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All Key Findings include a description of confidence. Where it is considered scientifically justified to report the likelihood of particular impacts within the range of possible outcomes, Key Findings also include a likelihood designation.

Confidence and likelihood levels are based on the expert judgment of the author team. They determined the appropriate level of confidence or likelihood by assessing the available literature, determining the quality and quantity of available evidence, and evaluating the level of agreement across different studies. Often, the underlying studies provided their own estimates of uncertainty and confidence intervals. When available, these confidence intervals were assessed by the authors in making their own expert judgments. For specific descriptions of the process by which the author team came to agreement on the Key Findings and the assessment of confidence and likelihood, see the Traceable Accounts in each chapter.

In addition to the use of systematic language to convey confidence and likelihood information, this report attempts to highlight aspects of the science that are most relevant for supporting the assessment (for example, in the upcoming Fourth National Climate Assessment) of key societal risks posed by climate change. This includes attention to trends and changes in the tails of the probability distribution of future climate change and its proximate impacts (for example, on sea level or temperature and precipitation extremes) and on defining plausible bounds for the magnitude of future changes, since many key risks are disproportionately determined by plausible low-probability, high-consequence outcomes. Therefore, in addition to presenting the expert judgment on the "most likely" range of projected future climate outcomes, where appropriate, this report also provides information on the outcomes lying outside this range which nevertheless cannot be ruled out, and may therefore be relevant for assessing overall risk. In some cases, this involves an evaluation of the full range of information contained in the ensemble of climate models used for this report, and in other cases will involve the consideration of additional lines of scientific evidence beyond the models.

Complementing this use of risk-focused language and presentation around specific scientific findings in the report, Chapter 15: Potential Surprises provides an overview of potential low probability/high consequence "surprises" resulting from climate change, including thresholds, also called tipping points, in the climate system and the compounding effects of multiple, interacting climate change impacts whose consequences may be much greater than the sum of the individual impacts. Chapter 15 also highlights critical knowledge gaps that determine the degree to which such high-risk tails and bounding scenarios can be precisely defined, including missing processes and feedbacks that make it more likely than not that climate models currently underestimate the potential for high-end changes, reinforcing the need to look beyond the central tendencies of model projections to meaningfully assess climate change risk.

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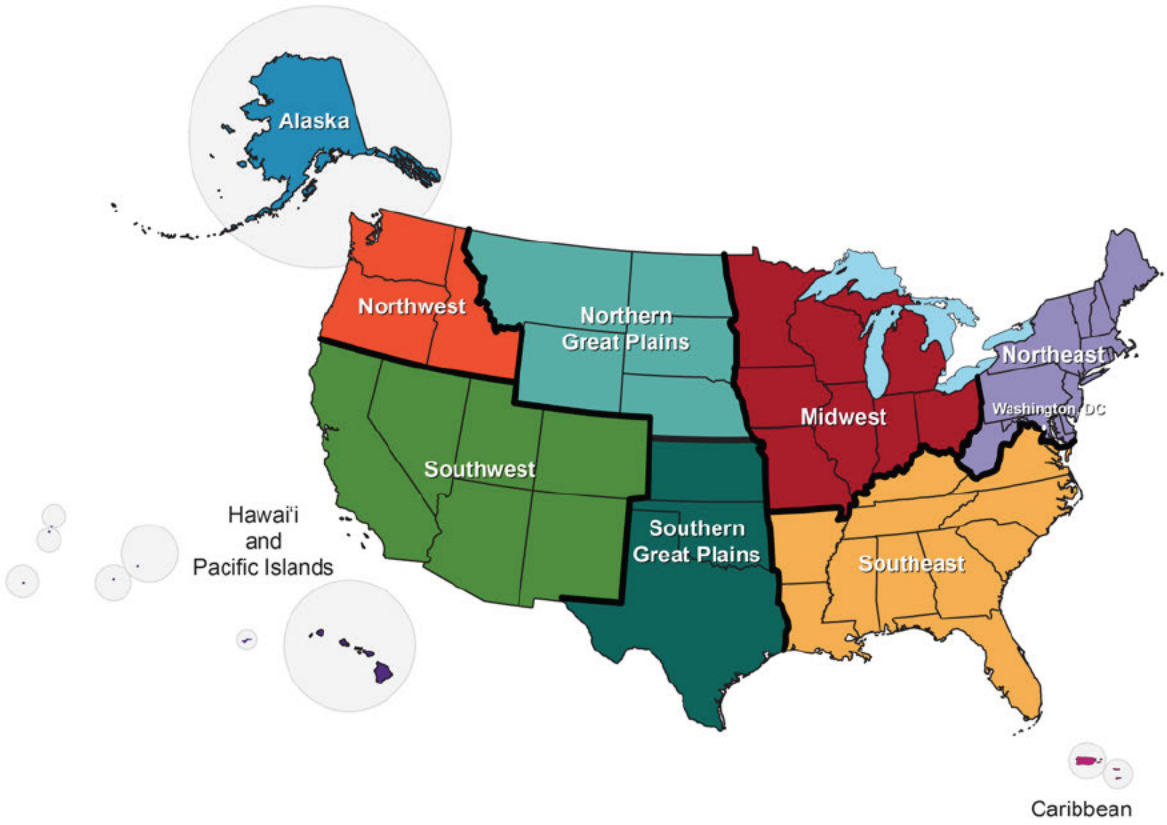

Figure 1. Map of the ten regions of the United States used throughout the Climate Science Special Report. Regions are similar to that used in the Third National Climate Assessment except that 1) the Great Plains are split into the Northern Great Plains and Southern Great Plains, and 2) the Caribbean islands have been split from the Southeast region. (Figure source: adapted from Melillo et al. 2014).

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

Likelihood	
Virtually Certain	99%–100%
Extremely Likely	95%–100%
Very Likely	90%–100%
Likely	66%–100%
About as Likely as Not	33%–66%
Unlikely	0%–33%
Very Unlikely	0%–10%
Extremely Unlikely	0%–5%
Exceptionally Unlikely	0%–1%

Figure 2. Confidence levels and likelihood statements used in the report. (Figure source: adapted from USGCRP 2016 and IPCC 2013 (likelihoods use the broader range from the IPCC assessment). As an example, a 66%–100% probability can be interpreted as a likelihood of more than 2 out of 3 chances for this certainty.

Front Matter References

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Executive Summary

Introduction

New observations and new research have increased our understanding of past, current, and future climate change since the Third U.S. National Climate Assessment (NCA3) was published in May 2014. This Climate Science Special Report (CSSR) is designed to capture that new information and build on the existing body of science in order to summarize the current state of knowledge and provide the scientific foundation for the Fourth National Climate Assessment (NCA4).

Since NCA3, stronger evidence has emerged for continuing, rapid, human-caused warming of the global atmosphere and ocean. This report concludes that "it is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century. For the warming over the last century, there is no convincing alternative explanation supported by the extent of the observational evidence."

The last few years have also seen record-breaking, climate-related weather extremes, the three warmest years on record for the globe, and continued decline in arctic sea ice. These trends are expected to continue in the future over climate (multidecadal) timescales. Significant advances have also been made in our understanding of extreme weather events and how they relate to increasing global temperatures and associated climate changes. Since 1980, the cost of extreme events for the United States has exceeded $1.1 trillion, therefore better understanding of the frequency and severity of these events in the context of a changing climate is warranted.

Periodically taking stock of the current state of knowledge about climate change and putting new weather extremes, changes in sea ice, increases in ocean temperatures, and ocean acidification into context ensures that rigorous, scientifically-based information is available to inform dialogue and decisions at every level. Most of this special report is intended for those who have a technical background in climate science and to provide input to the authors of NCA4. In this Executive Summary, green boxes present highlights of the main report. These are followed by related points and selected figures providing more scientific details. The summary material on each topic presents the most salient points of chapter findings and therefore represents only a subset of the report's content. For more details, the reader is referred to the individual chapters. This report discusses climate trends and findings at several scales: global, nationwide for the United States, and for ten specific U.S. regions (shown in Figure 1 in the Guide to the Report). A statement of scientific confidence also follows each point in the Executive Summary. The confidence scale is described in the Guide to the Report. At the end of the Executive Summary and in Chapter 1: Our Globally Changing Climate, there is also a summary box highlighting the most notable advances and topics since NCA3 and since the 2013 Intergovernmental Panel on Climate Change (IPCC) report.

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Global and U.S. Temperatures Continue to Rise

Long-term temperature observations are among the most consistent and widespread evidence of a warming planet. Temperature (and, above all, its local averages and extremes) affects agricultural productivity, energy use, human health, water resources, infrastructure, natural ecosystems, and many other essential aspects of society and the natural environment. Recent data adds to the weight of evidence for rapid global-scale warming, the dominance of human causes, and the expected continuation of increasing temperatures, including more record-setting extremes. (Ch.1)

Changes in Observed and Projected Global Temperature

The global, long-term, and unambiguous warming trend has continued during recent years. Since the last National Climate Assessment was published, 2014 became the warmest year on record globally; 2015 surpassed 2014 by a wide margin; and 2016 surpassed 2015. Sixteen of the last 17 years are the warmest years on record for the globe. (Ch.1; Fig ES.1)

- Global annual-average temperature (as calculated from instrumental records over both land and oceans) has increased by more than 1.2°F (0.7°F) for the period 1986–2016 relative to 1901–1960; the linear regression change over the entire period from 1901–2016 is 1.8°F (1.0°C) (*very high confidence*; Fig. ES.1). Longer-term climate records over past centuries and millennia indicate that average temperatures in recent decades over much of the world have been much higher, and have risen faster during this time period, than at any time in the past 1,700 years or more, the time period for which the global distribution of surface temperatures can be reconstructed (*high confidence*). (Ch.1)

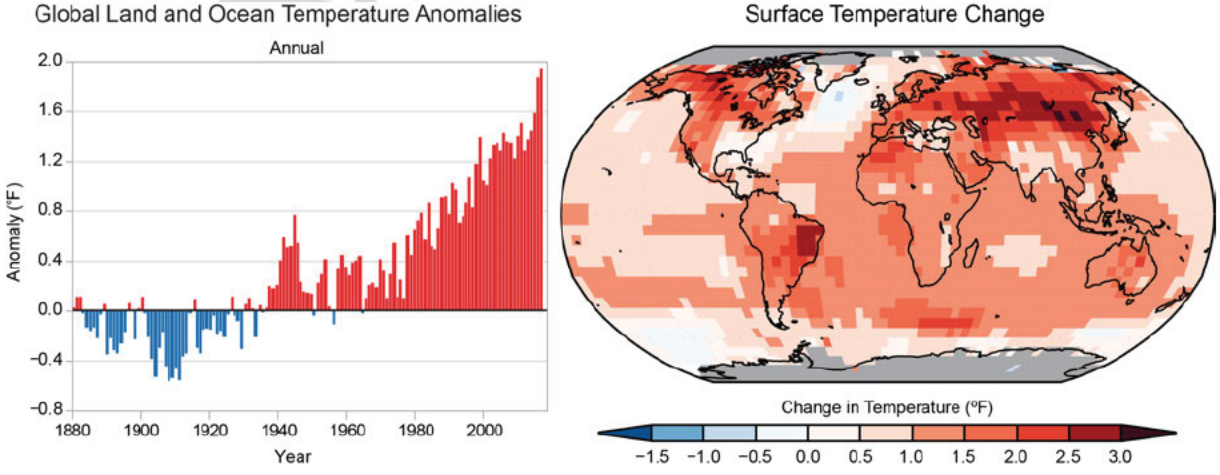

Figure ES.1 Global Temperatures Continue to Rise

Left: Global annual average temperature has increased by more than 1.2°F (0.7°C) for the period 1986–2016 relative to 1901–1960. Red bars show temperatures that were above the 1901–1960 average, and blue bars indicate temperatures below the average. Right: Surface temperature change (in °F) for the period 1986–2016 relative to 1901–1960. Grey indicates missing data. *From Figures 1.2. and 1.3 in Ch.1.*

- Many lines of evidence demonstrate that it is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century. Over the last century, there are no convincing alternative explanations supported by the extent of the observational evidence. Solar output changes and internal natural variability can only contribute marginally to the observed changes in climate over the last century, and we find no convincing evidence for natural cycles in the observational record that could explain the observed changes in climate. (*Very high confidence*) (Ch.1)

- The *likely* range of the human contribution to the global mean temperature increase over the period 1951–2010 is 1.1° to 1.4°F (0.6° to 0.8°C), and the central estimate of the observed warming of 1.2°F (0.65°C) lies within this range (*high confidence*). This translates to a *likely* human contribution of 92%–123% of the observed 1951–2010 change. The *likely* contributions of natural forcing and internal variability to global temperature change over that period are minor (*high confidence*). (Ch.3; Fig ES.2)

- Natural variability, including El Niño events and other recurring patterns of ocean–atmosphere interactions, impact temperature and precipitation, especially regionally, over timescales of months to years. The global influence of natural variability, however, is limited to a small fraction of observed climate trends over decades. (*Very high confidence*) (Ch.1)

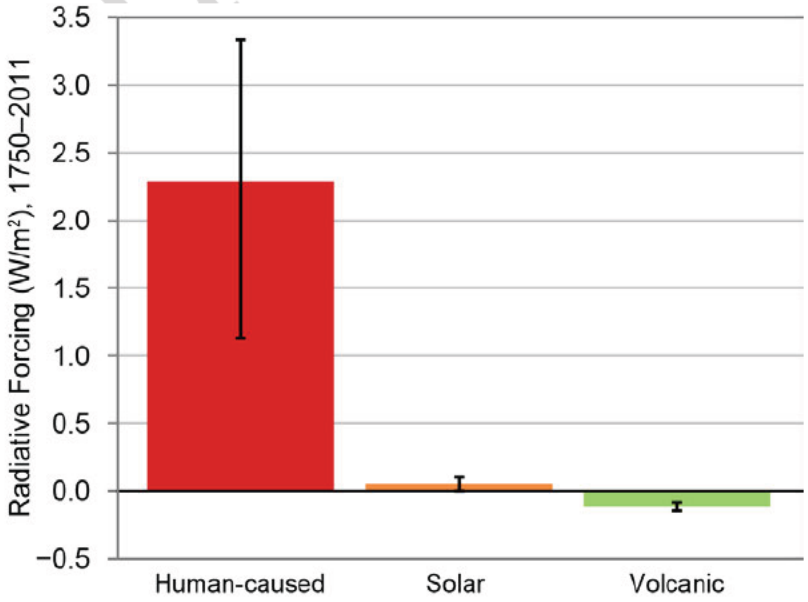

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Figure ES.2 Human Activities Are the Primary Driver of Recent Global Temperature Rise

Global annual average radiative forcing change from 1750 to 2011 due to human activities, changes in total solar irradiance, and volcanic emissions. Black bars indicate the uncertainty in each. Radiative forcing is a measure of the influence a factor (such as greenhouse gas emissions) has in changing the global balance of incoming and outgoing energy. Over this time period, solar forcing has oscillated on approximately an 11-year cycle between 0.11 and +0.19 W/m^2. Radiative forcing due to volcanic emissions is always negative (cooling) and can be very large immediately following significant eruptions but is short-lived. Over the industrial era, the largest volcanic forcing followed the eruption of Mt. Tambora in 1815 (11.6 W/m^2). This forcing declined to 4.5 W/m^2 in 1816, and to near-zero by 1820. Forcing due to human activities, in contrast, has becoming increasingly positive (warming) since about 1870, and has grown at an accelerated rate since about 1970. Radiative forcings greater than zero (positive forcings) produce climate warming; forcings less than zero (negative forcings) produce climate cooling. There are also natural variations in temperature and other climate variables which operate on annual to decadal time-scales. This natural variability contributes very little to climate trends over decades and longer. *Simplified from Figure 2.6 in Chapter 2. See Chapter 2 for more details.*

- Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades will depend primarily on the amount of greenhouse (heat-trapping) gases emitted globally and on the remaining uncertainty in the sensitivity of Earth's climate to those emissions (very *high confidence*). With significant reductions in the emissions of greenhouse gases, the global annually averaged temperature rise could be limited to 3.6°F (2°C) or less. Without major reductions in these emissions, the increase in annual average global temperatures relative to pre-industrial times could reach 9°F (5°C) or more by the end of this century. (Ch.1; Fig ES.3)

- If greenhouse gas concentrations were stabilized at their current level, existing concentrations would commit the world to at least an additional 1.1°F (0.6°C) of warming over this century relative to the last few decades (*high confidence* in continued warming, *medium confidence* in amount of warming. (Ch.4)

Sidebar: Scenarios Used in this Assessment

Projections of future climate conditions use a range of plausible future scenarios. Consistent with previous practice, this assessment relies on scenarios generated for the Intergovernmental Panel on Climate Change (IPCC). The IPCC completed its last assessment in 2013–2014, and its projections were based on updated scenarios, namely four "representative concentration pathways" (RCPs). The RCP scenarios are numbered according to changes in radiative forcing in 2100 relative to preindustrial conditions: +2.6, +4.5, +6.0 and +8.5 watts per square meter (W/m^2). Radiative forcing is a measure of the influence a factor (such as greenhouse gas emissions) has in changing the global balance of incoming and outgoing energy. Greenhouse gases (GHGs) in the atmosphere absorb most of the outgoing

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radiation, leading to a warming of the surface and atmosphere. Though multiple emissions pathways could lead to the same 2100 radiative forcing value, an associated pathway of CO_2 and other human-caused emissions of greenhouse gases, aerosols, and air pollutants has been selected for each RCP. RCP8.5 implies a future with continued high emissions growth, whereas the other RCPs represent different pathways of mitigating emissions. Figure ES.3 shows these emission pathways and the corresponding projected changes in global temperature.

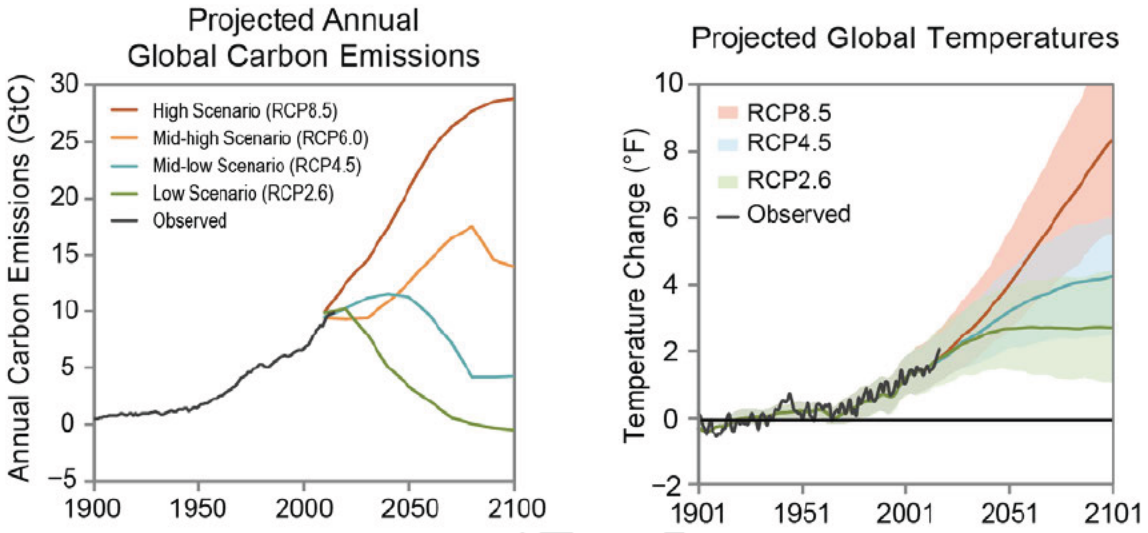

Figure ES.3. Greater Emissions Lead to Significantly More Warming.
The two panels above show annual historical and a range of plausible future carbon emissions in units of gigatons of carbon (GtC) per year (left) and the historical observed and future temperature change that would result for a range of future scenarios relative to the 1901–1960 average, based on the central estimate (lines) and a range (shaded areas, two standard deviations) as simulated by the full suite of CMIP5 global climate models (right). By 2081–2100, the projected range in global mean temperature change is 1.1°–4.3°F under the RCP2.6 scenario (0.6°–2.4°C, green), 2.4°–5.9°F under RCP4.5 (1.3°–3.3°C, blue), 3.0°–6.8°F under RCP6.0 (1.6°–3.8°C, not shown) and 5.0°–10.2°F under RCP8.5 (2.8°–5.7°C, orange). See the main report for more details on these scenarios and implications. *Based on Figure 4.1 in Chapter 4.*

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Changes in Observed and Projected U.S. Temperature

Average annual temperature over the contiguous United States has increased by 1.8°F (1.0°C) for the period 1901–2016 and is projected to continue to rise. (*Very high confidence*). (Ch.6; Fig ES.4)

- Average annual temperature over the contiguous United States has increased by 1.2°F (0.7°C) for the period 1986–2016 relative to 1901–1960 and by 1.8°F (1.0°C) based on a linear regression for the period 1901–2016 (*very high confidence*). Surface and satellite data are consistent in their depiction of rapid warming since 1979 (*high confidence*). Paleo-temperature evidence shows that recent decades are the warmest of the past 1,500 years (*medium confidence*) (Ch.6)

- Average annual temperature over the contiguous United States is projected to rise (*very high confidence*). Increases of about 2.5°F (1.4°C), relative to the recent past (average from 1976–2005) are projected for the next few decades in all emissions scenarios, implying recent record-setting years may be "common" in the near future (*high confidence*). Much larger rises are projected by late century: 2.8°–7.3°F (1.6°–4.1°C) in a lower emissions scenario (RCP4.5) and 5.8°–11.9°F (3.2°–6.6°C) in a higher emissions scenario (RCP8.5) (*high confidence*). (Ch.6; Fig ES.4)

- In the United States, the urban heat island effect results in daytime temperatures 0.9°–7.2°F (0.5°–4.0°C) higher and nighttime temperatures 1.8°– 4.5°F (1.0°–2.5°C) higher in urban areas, with larger temperature differences in humid regions (primarily in the eastern United States) and in cities with larger and denser populations. The urban heat island effect will strengthen in the future as the structure and spatial extent as well as population density of urban areas change and grow (*high confidence*). (Ch.10)

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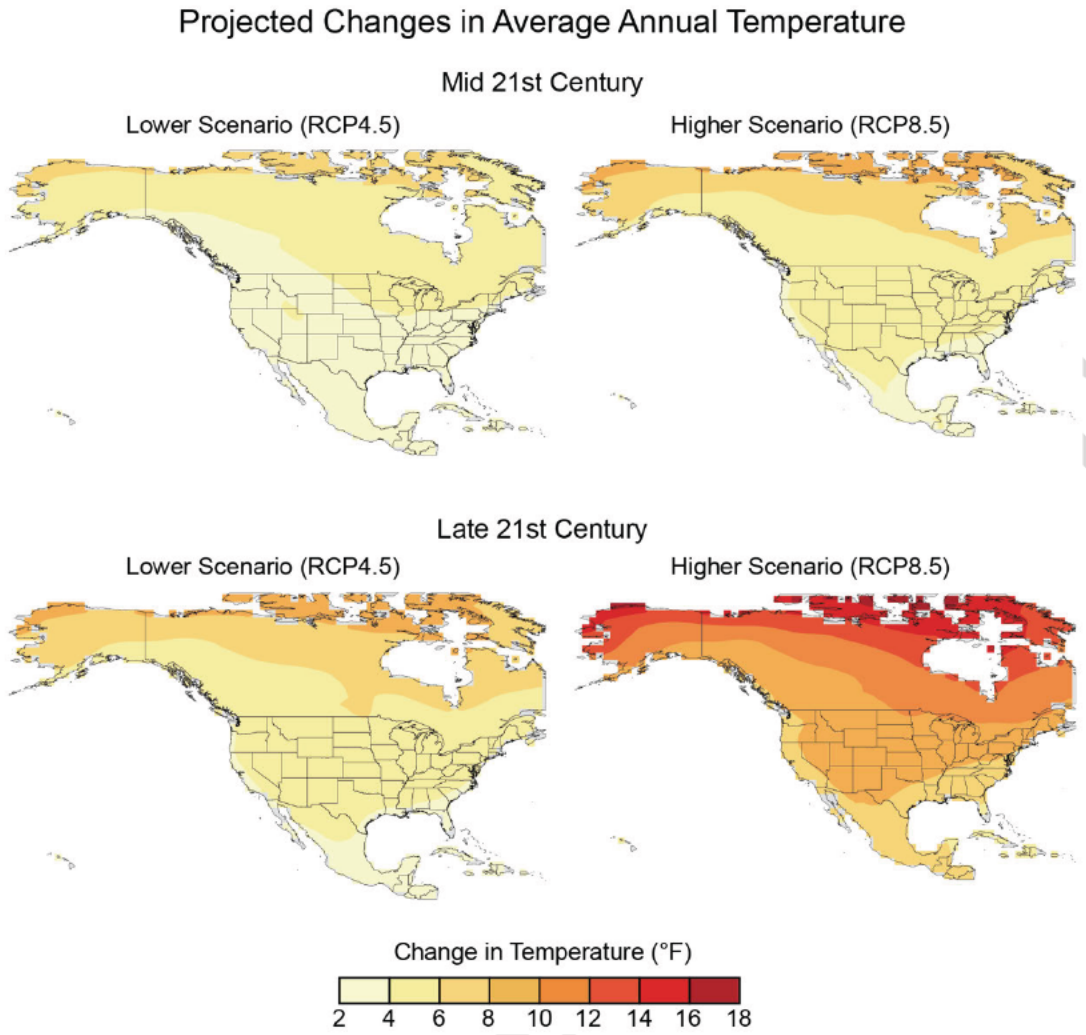

Figure ES.4 Significantly More Warming Occurs Under Higher Greenhouse Gas Concentration Scenarios

These maps show the projected changes in annual average temperatures for mid- and late-21st century for two future pathways. Changes are the differences between the average projected temperatures for mid-century (2036–2065; top), and late-century (2071–2100; bottom), and those observed for the near-present (1976–2005). *See Figure 6.7 in Chapter 6 for more details.*

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Many Temperature and Precipitation Extremes Are Becoming More Common

Temperature and precipitation extremes can affect water quality and availability, agricultural productivity, human health, vital infrastructure, iconic ecosystems and species, and the likelihood of disasters. Some extremes have already become more frequent, intense, or of longer duration, and many extremes are expected to continue to increase or worsen, presenting substantial challenges for built, agricultural, and natural systems. Some storm types such as hurricanes, tornadoes, and winter storms are also exhibiting changes that have been linked to climate change, although the current state of the science does not yet permit detailed understanding.

Observed Changes in Extremes

There have been marked changes in temperature extremes across the contiguous United States. The number of high temperature records set in the past two decades far exceeds the number of low temperature records. (*Very high confidence*) (Ch.6, Fig ES.5)

- The frequency of cold waves has decreased since the early 1900s, and the frequency of heat waves has increased since the mid-1960s (the Dust Bowl remains the peak period for extreme heat). (*Very high confidence*). (Ch.6)

- The frequency and intensity of extreme heat and heavy precipitation events are increasing in most continental regions of the world (*very high confidence*). These trends are consistent with expected physical responses to a warming climate. Climate model studies are also consistent with these trends, although models tend to underestimate the observed trends, especially for the increase in extreme precipitation events (*very high confidence* for temperature, *high confidence* for extreme precipitation). (Ch.1)

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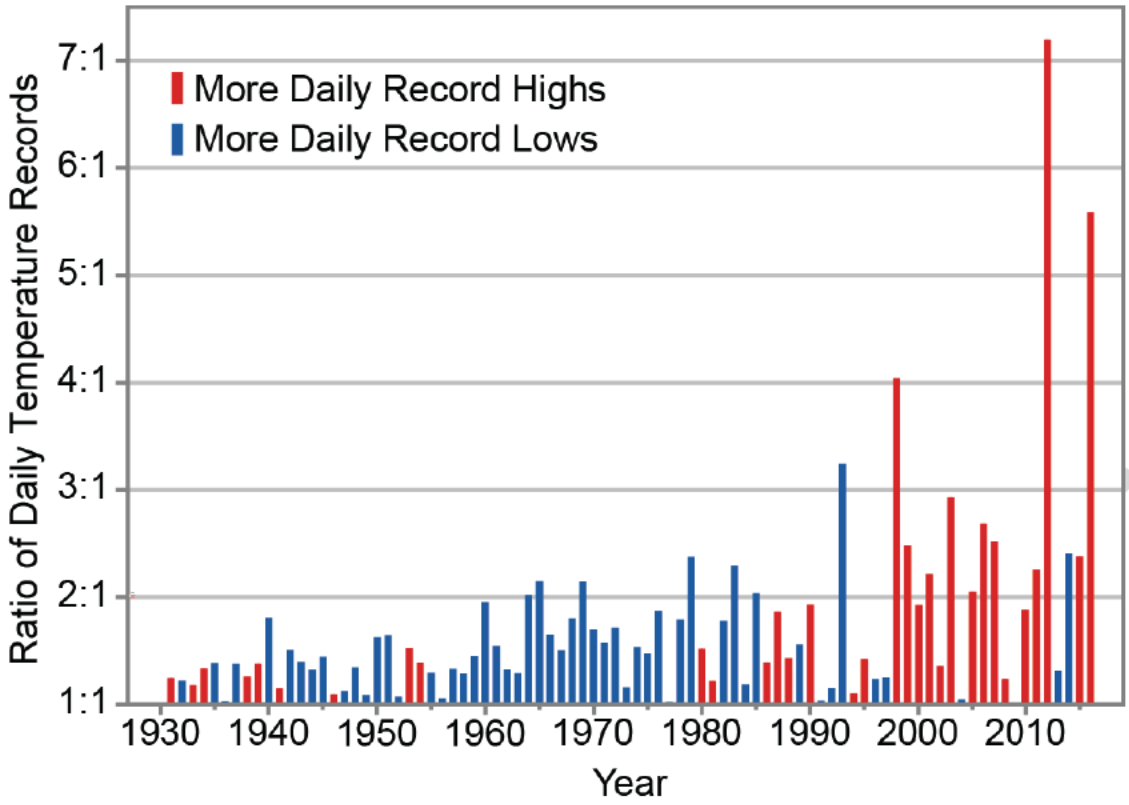

Figure ES.5: Record Warm Daily Temperatures Are Occurring More Often. Observed changes in the occurrence of record-setting daily temperatures in the contiguous United States. Red bars indicate a year with more daily record highs than daily record lows, while blue bars indicate a year with more record lows than highs. The height of the bar indicates the ratio of record highs to lows (red) or of record lows to highs (blue). For example, a ratio of 2:1 for a blue bar means that there were twice as many record daily lows as daily record highs that year. (Figure source: NOAA/NCEI). (*from Figure 6.5 in Chapter 6*)

Heavy precipitation events in most parts of the United States have increased in both intensity and frequency since 1901 (*high confidence*). There are important regional differences in trends, with the largest increases occurring in the northeastern United States (*high confidence*). (Ch.7; Fig ES.6)

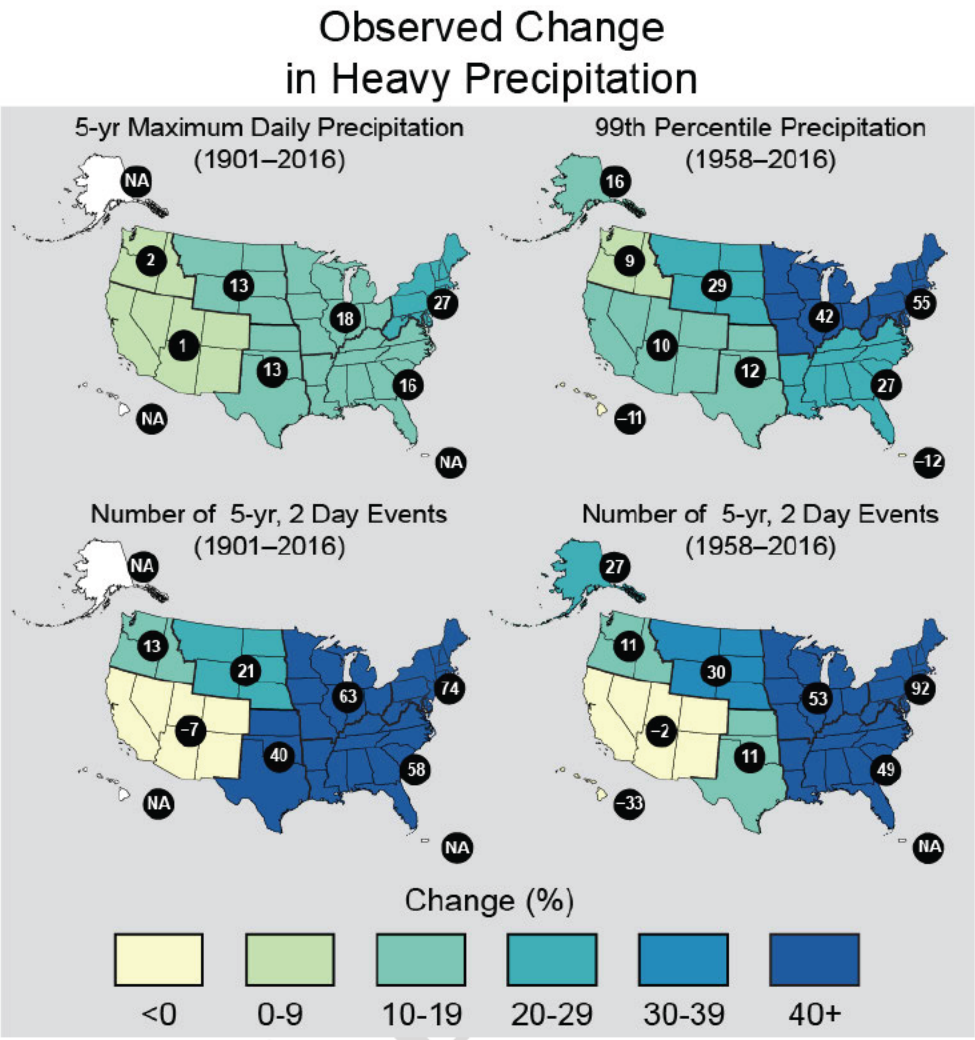

Figure ES.6: Extreme Precipitation Has Increased Across Much of the United States
These maps show the percentage change in several metrics of extreme precipitation by NCA4 region, including (upper left) the maximum daily precipitation in consecutive 5-year periods; (upper right) the amount of precipitation falling in daily events that exceed the 99th percentile of all non-zero precipitation days (top 1% of all daily precipitation events); (lower left) the number of 2-day events with a precipitation total exceeding the largest 2-day amount that is expected to occur, on average, only once every 5 years, as calculated over 1901-2016; and (lower right) the number of 2-day events with a precipitation total exceeding the largest 2-day amount that is expected to occur, on average, only once every 5 years, as calculated over 1958–2016. The number in each black circle is the percent change over the entire period, either 1901–2016 or 1958–2016. Note that Alaska and Hawai'i are not included in the 1901–2016 maps owing to a lack of observations in the earlier part of the 20th century. *(Figure source: CICS-NC / NOAA NCEI). Based on figure 7.4 in Chapter 7.*

- Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record. (*Very high confidence*) (Ch. 8)

- Northern Hemisphere spring snow cover extent, North America maximum snow depth, snow water equivalent in the western United States, and extreme snowfall years in the southern and western United States, have all declined, while extreme snowfall years in parts of the northern United States have increased. (*Medium confidence*). (Ch.7)

- There has been a trend toward earlier snowmelt and a decrease in snowstorm frequency on the southern margins of climatologically snowy areas (*medium confidence*). Winter storm tracks have shifted northward since 1950 over the Northern Hemisphere (*medium confidence*). Potential linkages between the frequency and intensity of severe winter storms in the United States and accelerated warming in the Arctic have been postulated, but they are complex, and, to some extent, contested, and confidence in the connection is currently *low*. (Ch.9)

- Tornado activity in the United States has become more variable, particularly over the 2000s, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). Confidence in past trends for hail and severe thunderstorm winds, however, is *low* (Ch.9)

Projected Changes in Extremes

- The frequency and intensity of extreme temperature events are *virtually certain* to increase in the future as global temperature increases (*high confidence*). Extreme precipitation events will *very likely* continue to increase in frequency and intensity throughout most of the world (*high confidence*). Observed and projected trends for some other types of extreme events, such as floods, droughts, and severe storms, have more variable regional characteristics. (Ch.1)

Extreme temperatures in the contiguous United States are projected to increase even more than average temperatures (*very high confidence)*. (Ch.6)

- Both extremely cold days and extremely warm days are expected to become warmer. Cold waves are predicted to become less intense while heat waves will become more intense. The number of days below freezing is projected to decline while the number above 90°F will rise. *(Very high confidence)* (Ch.6)

- The frequency and intensity of heavy precipitation events in the United States are projected to continue to increase over the 21st century (*high confidence*). There are, however, important regional and seasonal differences in projected changes in total precipitation: the northern United States, including Alaska, is projected to receive more precipitation in the winter and spring, and parts of the southwestern United

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States are projected to receive less precipitation in the winter and spring (*medium confidence*). (Ch.7)

- The frequency and severity of landfalling "atmospheric rivers" on the U.S. West Coast (narrow streams of moisture that account for 30%–40% of precipitation and snowpack in the region and are associated with severe flooding events) will increase as a result of increasing evaporation and resulting higher atmospheric water vapor that occurs with increasing temperature. (*Medium confidence*) (Ch.9)

- Projections indicate large declines in snowpack in the western United States and shifts to more precipitation falling as rain than snow in the cold season in many parts of the central and eastern United States (*high confidence*). (Ch.7)

- Substantial reductions in western U.S. winter and spring snowpack are projected as the climate warms. Earlier spring melt and reduced snow water equivalent have been formally attributed to human induced warming (*high confidence*) and will *very likely* be exacerbated as the climate continues to warm (*very high confidence*). Under higher emissions scenarios, and assuming no change to current water resources management, chronic, long-duration hydrological drought is increasingly possible by the end of this century (*very high confidence*). (Ch.8)

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Future decreases in surface soil moisture from human activities over most of the United States are *likely* as the climate warms under the higher emissions scenarios. (*Medium confidence*) (Ch.8)

- The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (*High confidence*) (Ch.8)

- The incidence of large forest fires in the western United States and Alaska has increased since the early 1980s (*high confidence*) and is projected to further increase in those regions as the climate warms, with profound changes to certain ecosystems (*medium confidence*). (Ch.8)

- Both physics and numerical modeling simulations (in general) indicate an increase in tropical cyclone intensity in a warmer world, and the models generally show an increase in the number of very intense tropical cyclones. For Atlantic and eastern North Pacific hurricanes and western North Pacific typhoons, increases are projected in precipitation rates (*high confidence*) and intensity *(medium confidence)*. The frequency of the most intense of these storms is projected to increase in the Atlantic

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and western North Pacific (*low confidence*) and in the eastern North Pacific (*medium confidence*). (Ch.9)

******BOX ES.1 ******

The Connected Climate System: Distant Changes Affect the United States

Weather conditions and the ways they vary across regions and over the course of the year are influenced, in the United States as elsewhere, by a range of factors, including local conditions (such as topography and urban heat islands), global trends (such as human-caused warming), and global and regional circulation patterns, including cyclical and chaotic patterns of natural variability within the climate system. For example, during an El Niño year, winters across the southwestern United States are typically wetter than average, and global temperatures are higher than average. During a La Niña year, conditions across the southwestern United States are typically dry, and there tends to be a lowering of global temperatures (Fig. ES.7).

El Niño is not the only repeating pattern of natural variability in the climate system. Other important patterns include the North Atlantic Oscillation (NAO)/Northern Annular Mode (NAM) that particularly affects conditions on the U.S. East Coast, and the North Pacific Oscillation (NPO) and Pacific North American Pattern (PNA) that especially affect conditions in Alaska and the U.S. West Coast. These patterns are closely linked to other atmospheric circulation phenomena like the position of the jet streams. Changes in the occurrence of these patterns or their properties have contributed to recent U.S. temperature and precipitation trends (*medium confidence*) although confidence is low regarding the size of the role of human activities in these changes. (Ch.5)

Understanding the full scope of human impacts on climate requires a global focus because of the interconnected nature of the climate system. For example, the climate of the Arctic and the climate of the continental United States are connected through atmospheric circulation patterns. While the Arctic may seem remote to most Americans, the climatic effects of perturbations to arctic sea ice, land ice, surface temperature, snow cover, and permafrost affect the amount of warming, sea level change, carbon cycle impacts, and potentially even weather patterns in the lower 48 states. The Arctic is warming at a rate approximately twice as fast as the global average and, if it continues to warm at the same rate, Septembers will be nearly ice-free in the Arctic Ocean sometime between now and the 2040s (see ES.10). The important influence of Arctic climate change on Alaska is apparent; the influence of Arctic changes on U.S. weather over the coming decades remains an open question with the potential for significant impact. (Ch.11)

Changes in the Tropics can also impact the rest of the globe, including the United States. There is growing evidence that the Tropics have expanded poleward by about 70 to 200 miles in each hemisphere over the period 1979–2009, with an accompanying shift of the subtropical dry zones, midlatitude jets, and storm tracks (*medium to high confidence*). Human activities

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have played a role in the change (*medium confidence*), although confidence is presently low regarding the magnitude of the human contribution relative to natural variability (Ch.5).

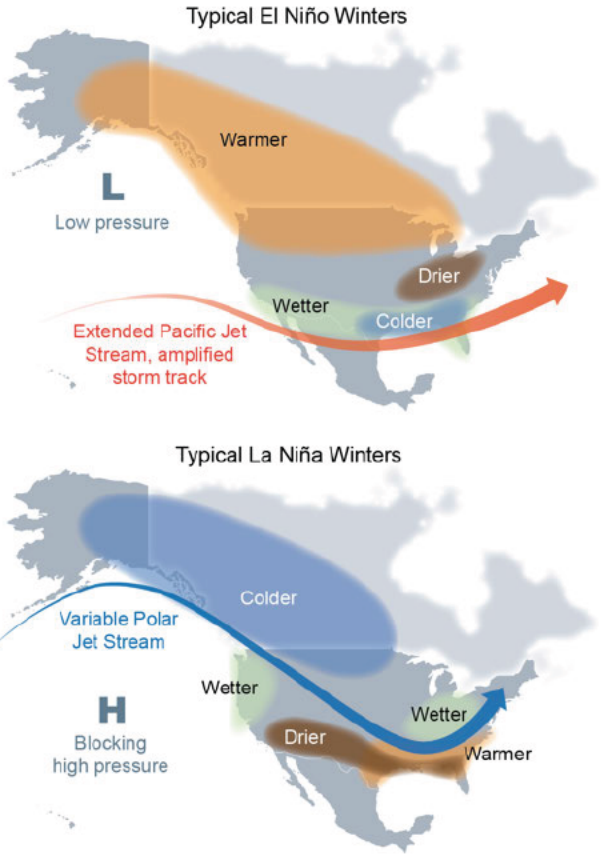

Figure ES.7. Large-Scale Patterns of Natural Variability Affect U.S. Climate
For example, this figure illustrates the typical January–March weather anomalies and atmospheric circulation during moderate to strong (top) El Niño and (bottom) La Niña. These influences over the United States often occur most strongly during the cold season. *From Figure 5.2 in Chapter 5.*

******END BOX ES.1******

Oceans Are Rising, Warming, and Becoming More Acidic

Oceans occupy two-thirds of the planet's surface and host unique ecosystems and species, including those important for global commercial and subsistence fishing. Understanding climate impacts on the ocean and the ocean's feedbacks to the climate system is critical for a comprehensive understanding of current and future changes in climate.

Global Ocean heat

The world's oceans have absorbed about 93% of the excess heat caused by greenhouse gas warming since the mid-20th century, making them warmer and altering global and regional climate feedbacks. (*Very high confidence*) (Ch.13)

- Ocean heat content has increased at all depths since the 1960s and surface waters have warmed by about 1.3°±0.1°F (0.7°±0.08°C) per century globally since 1900 to 2016. Under high emissions scenarios, a global increase in average sea surface temperature of 4.9°±1.3°F (2.7°±0.7°C) is projected by 2100. (*Very high confidence*). (Ch.13)

Global and Regional Sea Level Rise

Global mean sea level (GMSL) has risen by about 7–8 inches (about 16-21 cm) since 1900, with about 3 of those inches (about 7 cm) occurring since 1993 *(very high confidence)*. (Ch.12)

- Human-caused climate change has made a substantial contribution to GMSL rise since 1900 *(high confidence)*, contributing to a rate of rise that is greater than during any preceding century in at least 2,800 years *(medium confidence)*. (Ch.12; Fig ES.8)

- Relative to the year 2000, GMSL is *very likely* to rise by 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1–4 feet (30–130 cm) by 2100 *(very high confidence* in lower bounds*; medium confidence* in upper bounds for 2030 and 2050*; low* confidence in upper bounds for 2100*)*. Future emissions pathways have little effect on projected GMSL rise in the first half of the century, but significantly affect projections for the second half of the century *(high confidence)*. (Ch.12)

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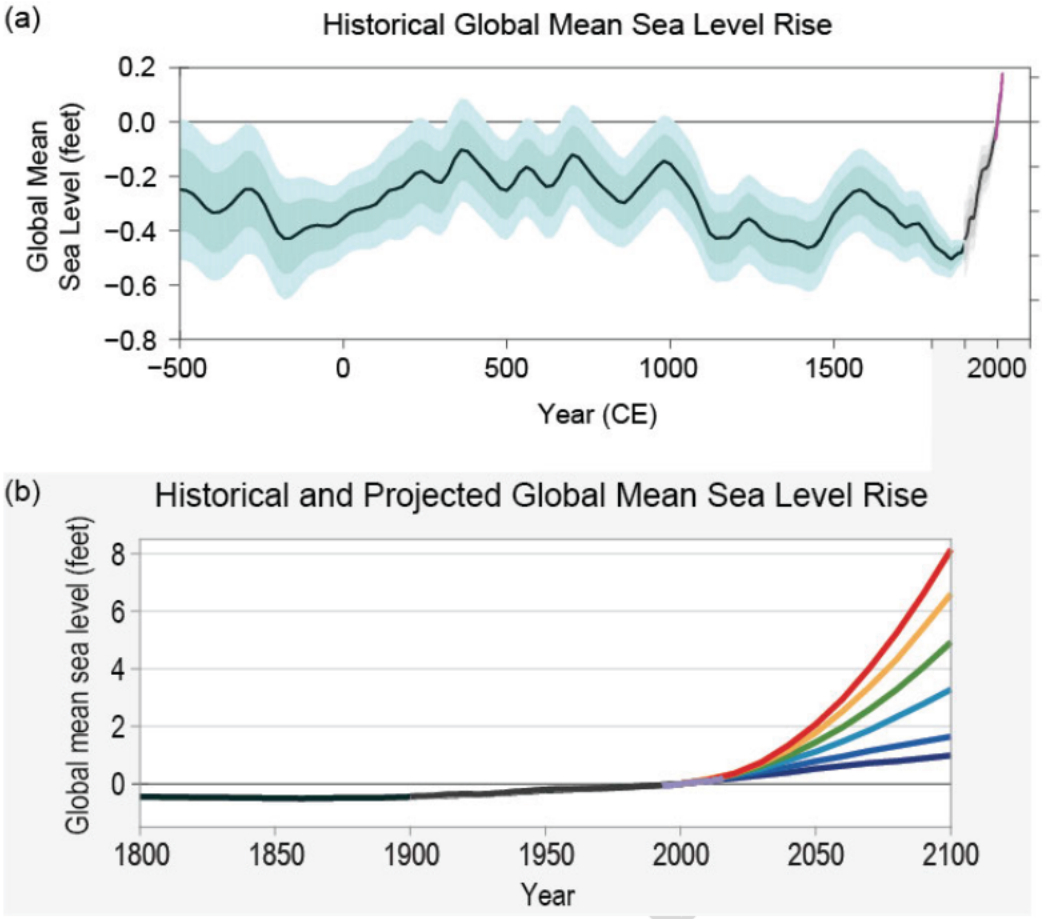

Figure ES.8 Recent Sea Level Rise Fastest for Over 2,000 Years

The top panel shows observed and reconstructed mean sea level for the last 2,500 years. The bottom panel shows projected mean sea level for six future scenarios. The six scenarios—spanning a range designed to inform a variety of decision makers—extend from a low scenario, consistent with continuation of the rate of sea level rise over the last quarter century, to an extreme scenario, assuming rapid mass loss from the Antarctic ice sheet. Note that the scale in the bottom graphic is three times greater than in the top graph. In both panels, the steep slope at the right of the graph depicts rapid sea level rise. *Based on Figure 12.2 and 12.4 in Chapter 12. See the main report for more details.*

- Emerging science regarding Antarctic ice sheet stability suggests that, for high emissions scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed. Regardless of emission pathway, it is *extremely likely* that GMSL rise will continue beyond 2100 (*high confidence*). (Ch.12)

- Relative sea level rise in this century will vary along U.S. coastlines due, in part, to changes in Earth's gravitational field and rotation from melting of land ice, changes in ocean circulation, and vertical land motion (*very high confidence*). For almost all future GMSL rise scenarios, relative sea level rise is *likely* to be greater than the global average in the U.S. Northeast and the western Gulf of Mexico. In intermediate and low GMSL rise scenarios, relative sea level rise is *likely* to be less than the global average

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in much of the Pacific Northwest and Alaska. For high GMSL rise scenarios, relative sea level rise is *likely* to be higher than the global average along all U.S. coastlines outside Alaska. Almost all U.S. coastlines experience more than global mean sea level rise in response to Antarctic ice loss, and thus would be particularly affected under extreme GMSL rise scenarios involving substantial Antarctic mass loss *(high confidence)*. (Ch.12)

Coastal Flooding

- As sea levels have risen, the number of tidal floods each year that cause minor impacts (also called "nuisance floods") have increased 5- to 10-fold since the 1960s in several U.S. coastal cities (*very high confidence*). Rates of increase are accelerating in over 25 Atlantic and Gulf Coast cities (*very high confidence*). Tidal flooding will continue increasing in depth, frequency, and extent this century (*very high confidence*). (Ch.12)

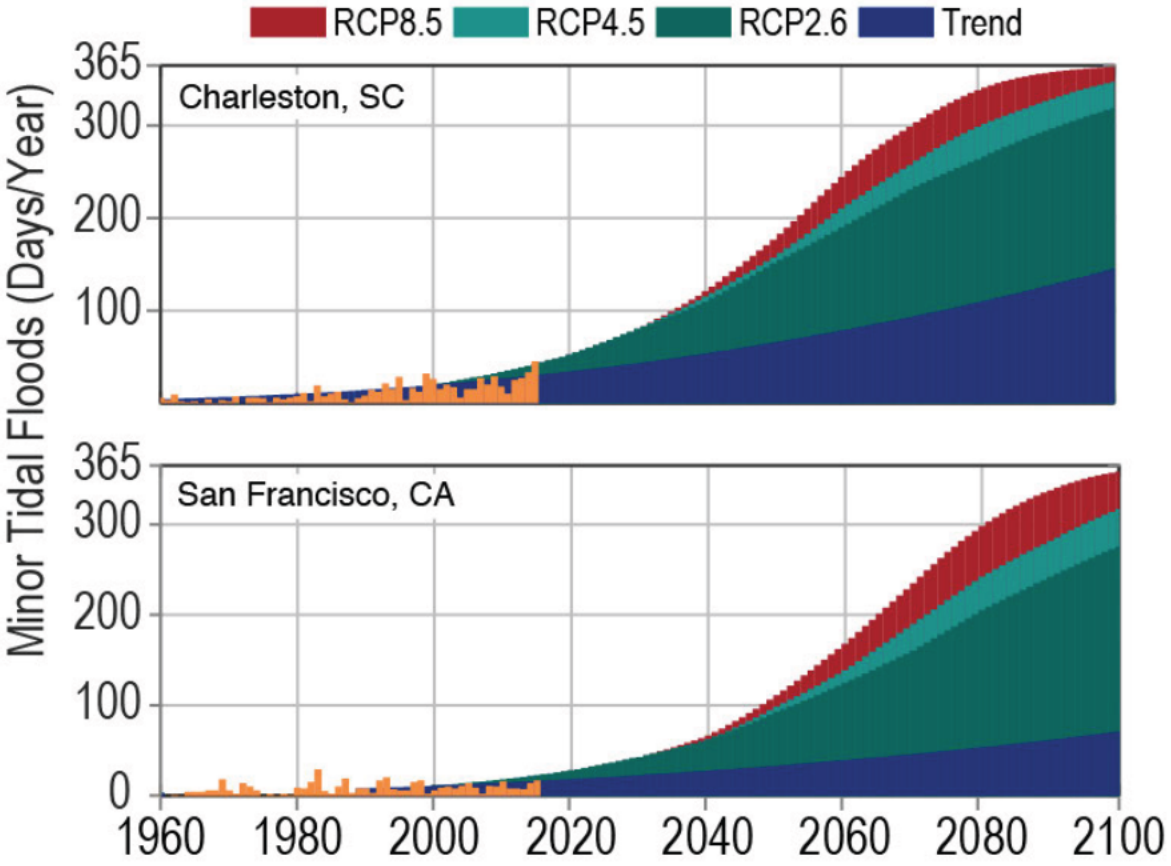

Figure ES. 9 "Nuisance Flooding" Increases Across the United States
Annual occurrences of tidal floods (days per year), also called sunny-day or nuisance flooding, have increased for some U.S. coastal cities. Historical exceedances (orange bars) for two of the locations—Charleston, SC and San Francisco, CA—and future projections through 2100 based upon the continuation of the historical trend (blue) and under median RCP2.6, 4.5 and 8.5 conditions. (From *Figure 12.5, Chapter 12).*

- Assuming storm characteristics do not change, sea level rise will increase the frequency and extent of extreme flooding associated with coastal storms, such as hurricanes and nor'easters (*very high confidence*). A projected increase in the intensity of hurricanes in the North Atlantic could increase the probability of extreme flooding along most of the U.S. Atlantic and Gulf Coast states beyond what would be projected based solely on RSL rise. However, there is *low confidence* in the magnitude of the increase in intensity and the associated flood risk amplification, and these effects could be offset or amplified by other factors, such as changes in storm frequency or tracks. (Ch.12; ES. 9)

Global Ocean Circulation

- The potential slowing of the Atlantic Meridional Overturning Circulation (AMOC; of which the Gulf Stream is one component)—as a result of increasing ocean heat content and freshwater driven buoyancy changes—could have dramatic climate feedbacks as the ocean absorbs less heat and CO_2 from the atmosphere. This slowing would also affect the climates of North America and Europe. Any slowing documented to date cannot be directly tied to human-caused forcing primarily due to lack of adequate observational data and to challenges in modeling ocean circulation changes. Under a high emissions scenario (RCP8.5), it is likely that the AMOC will weaken over the 21st century by 12% to 54% (*low confidence*). (Ch.13)

Global and Regional Ocean Acidification

The world's oceans are currently absorbing more than a quarter of the CO_2 emitted to the atmosphere annually from human activities, making them more acidic (*very high confidence*), with potential detrimental impacts to marine ecosystems. (Ch.13)

- Higher-latitude systems typically have a lower buffering capacity against changing acidity, exhibiting seasonally corrosive conditions sooner than low-latitude systems. The rate of acidification is unparalleled in at least the past 66 million years (*medium confidence*). Under RCP8.5, the global average surface ocean acidity is projected to increase by 100% to 150% (*high confidence*). (Ch.13)

- Acidification is regionally greater than the global average along U.S. coastal systems as a result of upwelling (e.g., in the Pacific Northwest) (*high confidence*), changes in freshwater inputs (e.g., in the Gulf of Maine) (*medium confidence*), and nutrient input (e.g., in urbanized estuaries) (*high confidence*). (Ch.13)

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Ocean Oxygen

- Increasing sea surface temperatures, rising sea levels, and changing patterns of precipitation, winds, nutrients, and ocean circulation are contributing to overall declining oxygen concentrations at intermediate depths in various ocean locations and in many coastal areas. Over the last half century, major oxygen losses have occurred in inland seas, estuaries, and in the coastal and open ocean (*high confidence*). Ocean oxygen levels are projected to decrease by as much as 3.5% under the RCP8.5 scenario by 2100 relative to preindustrial values (*high confidence*). *(Ch.13)*

Climate Change in Alaska and across the Arctic Continues to Outpace Global Climate Change

Residents of Alaska are on the front lines of climate change. Crumbling buildings, roads, and bridges and eroding shorelines are commonplace. Accelerated melting of multiyear sea ice cover, mass loss from the Greenland Ice Sheet, reduced snow cover, and permafrost thawing are stark examples of the rapid changes occurring in the Arctic. Furthermore, because elements of the climate system are interconnected (see Box ES.1), changes in the Arctic influence climate conditions outside the Arctic.

Arctic Temperature Increases

Annual average near-surface air temperatures across Alaska and the Arctic have increased over the last 50 years at a rate more than twice as fast as the global average temperature. (*Very high confidence*) (Ch.11)

- Rising Alaskan permafrost temperatures are causing permafrost to thaw and become more discontinuous; this process releases additional carbon dioxide and methane resulting in additional warming (*high confidence*). The overall magnitude of the permafrost-carbon feedback is uncertain (Ch.2); however, it is clear that these emissions have the potential to complicate the ability to meet policy goals for the reduction of greenhouse gas concentrations. (Ch.11)

- Atmospheric circulation patterns connect the climates of the Arctic and the contiguous United States. Evidenced by recent record warm temperatures in the Arctic and emerging science, the midlatitude circulation has influenced observed arctic temperatures and sea ice (*high confidence*). However, confidence is low regarding whether or by what mechanisms observed arctic warming may have influenced the midlatitude circulation and weather patterns over the continental United States. The

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influence of arctic changes on U.S. weather over the coming decades remains an open question with the potential for significant impact. (Ch.11)

Arctic Land Ice Loss

- Arctic land ice loss observed in the last three decades continues, in some cases accelerating (*very high confidence*). It is *virtually certain* that Alaska glaciers have lost mass over the last 50 years, with each year since 1984 showing an annual average ice mass less than the previous year. Over the satellite record, average ice mass loss from Greenland was −269 Gt per year between April 2002 and April 2016, accelerating in recent years (*high confidence)*. (Ch.11)

Arctic Sea Ice Loss

Since the early 1980s, annual average arctic sea ice has decreased in extent between 3.5% and 4.1% per decade, has become thinner by between 4.3 and 7.5 feet, and is melting at least 15 more days each year. September sea ice extent has decreased between 10.7% and 15.9% per decade. (*Very high confidence*) (Ch.11)

- Arctic sea ice loss is expected to continue through the 21st century, *very likely* resulting in nearly sea ice-free late summers by the 2040s (*very high confidence*). (Ch.11)

- It is *virtually certain* that human activities have contributed to Arctic surface temperature warming, sea ice loss since 1979, glacier mass loss, and northern hemisphere snow extent decline observed across the Arctic (*very high confidence*). Human activities have *likely* contributed to more than half of the observed September sea ice decline since 1979 (*high confidence*). (Ch.11)

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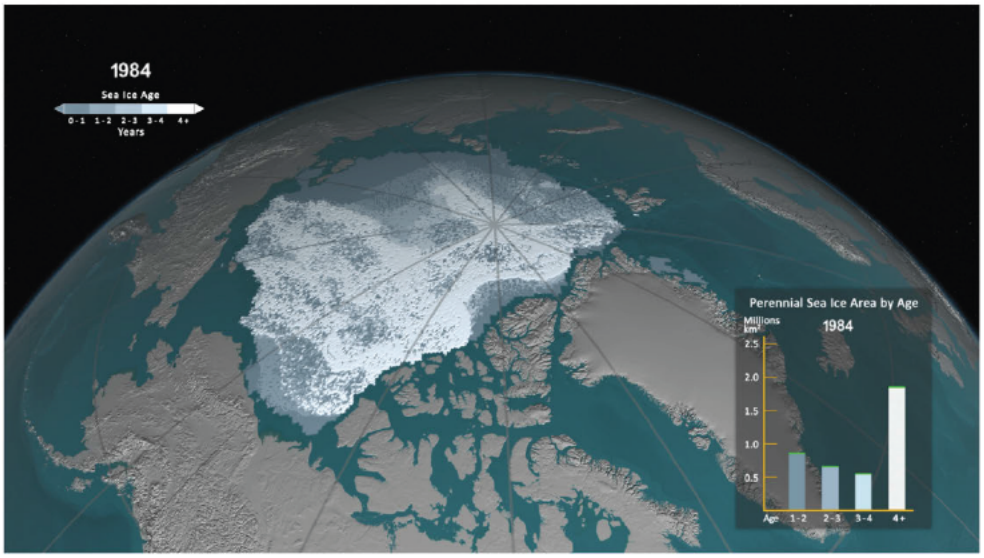
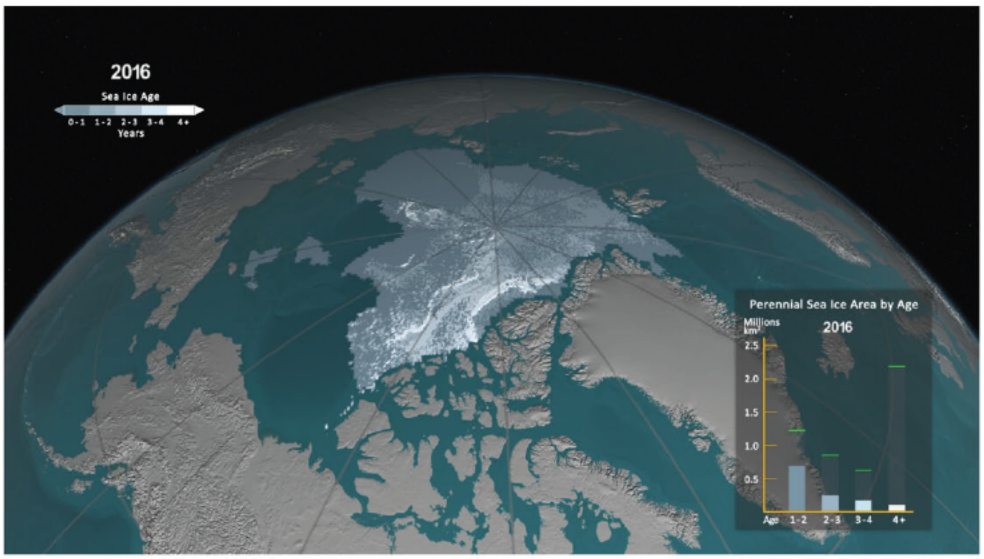
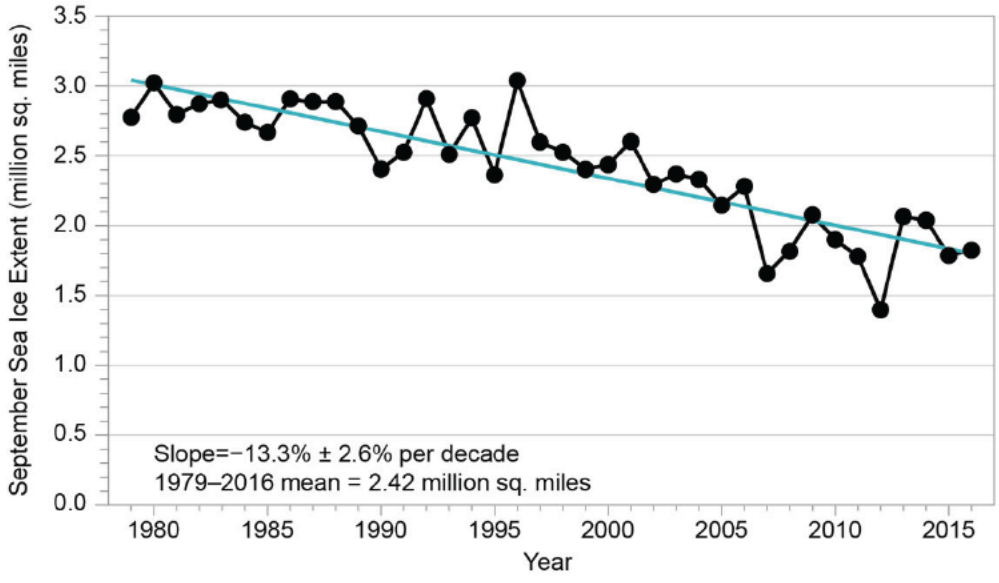

1984
Sea Ice Age
0-1 1-2 2-3 3-4 4+
Years
Perennial Sea Ice Area by Age
Millions km²
1984
2.5
2.0
1.5
1.0
0.5
Age 1-2 2-3 3-4 4+


2016
Sea Ice Age
0-1 1-2 2-3 3-4 4+
Years
Perennial Sea Ice Area by Age
Millions km²
2016
2.5
2.0
1.5
1.0
0.5
Age 1-2 2-3 3-4 4+


September Sea Ice Extent (million sq. miles)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Slope=−13.3% ± 2.6% per decade
1979–2016 mean = 2.42 million sq. miles
1980
1985
1990
1995
2000
2005
2010
2015
Year

1

Figure ES.10 Multiyear Sea Ice Has Declined Dramatically

September sea ice extent and age shown for (a) 1984 and (b) 2016, illustrating significant reductions in sea ice extent and age (thickness). The bar graph in the lower right of each panel illustrates the sea ice area (unit: million km^2) covered within each age category (> 1 year), and the green bars represent the maximum extent for each age range during the record. The year 1984 is representative of September sea ice characteristics during the 1980s. The years 1984 and 2016 are selected as endpoints in the time series; a movie of the complete time series is available at http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4489. (c) Shows the satellite-era arctic sea ice areal extent trend from 1979 to 2016 for September (unit: million mi^2)

From Figure 11.1 in Chapter 11.

Limiting Globally Averaged Warming to 2°C (3.6°F) Will Require Major Reductions in Emissions

Human activities are now the dominant cause of the observed trends in climate. For that reason, future climate projections are based on scenarios of how greenhouse gas emissions will continue to affect the climate over the remainder of this century and beyond (see Sidebar: Scenarios Used in this Assessment). There remains significant uncertainty about future emissions due to changing economic, political, and demographic factors. For that reason, this report quantifies possible climate changes for a broad set of plausible future scenarios through the end of the century. (Ch.2, 4, 14)

The observed increase in global carbon emissions over the past 15–20 years has been consistent with higher scenarios (*very high confidence*). In 2014 and 2015, emission growth rates slowed as economic growth has become less carbon-intensive (*medium confidence*). Even if this slowing trend continues, however, it is not yet at a rate that would meet the long-term temperature goal of the Paris Agreement of holding the increase in the global average temperature to well below 3.6°F (2°C) above preindustrial levels (*high confidence*). (Ch.4)

- Global mean atmospheric carbon dioxide (CO_2) concentration has now passed 400 ppm, a level that last occurred about 3 million years ago, when global average temperature and sea level were significantly higher than today (*high confidence*). Continued growth in CO_2 emissions over this century and beyond would lead to an atmospheric concentration not experienced in tens of millions of years (*medium confidence*). The present-day emissions rate of nearly 10 GtC per year suggests that there is no climate analog for this century any time in at least the last 50 million years (*medium confidence*). (Ch.4)

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- Warming and associated climate effects from CO_2 emissions persist for decades to millennia. In the near-term, changes in climate are determined by past and present greenhouse gas emissions modified by natural variability. Reducing the total concentration of atmospheric CO_2 is necessary to limit near-term climate change and stay below long-term warming targets (such as the oft-cited 3.6°F [2°C] goal). Other greenhouse gases (e.g., methane) and black carbon aerosols exert stronger warming effects than CO_2 on a per ton basis, but they do not persist as long in the atmosphere (Ch.2); therefore, mitigation of non-CO_2 species contributes substantially to near-term cooling benefits but cannot be relied upon for ultimate stabilization goals. (*Very high confidence*) (Ch.14)

- Stabilizing global mean temperature below long-term warming targets requires an upper limit on the accumulation of CO_2 in the atmosphere. The relationship between cumulative CO_2 emissions and global temperature response is estimated to be nearly linear. Nevertheless, in evaluating specific temperature targets, there are uncertainties about the exact amount of compatible human-caused CO_2 emissions due to uncertainties in climate sensitivity, the response of the carbon cycle including feedbacks, the amount of past CO_2 emissions, and the influence of past and future non-CO_2 species. (*Very high confidence*) (Ch.14)

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Choices made today will determine the magnitude of climate change risks beyond the next few decades. (Chs. 4,14)

- Stabilizing global mean temperature below 3.6°F (2°C) or lower relative to preindustrial levels requires significant reductions in net global CO_2 emissions relative to present-day values before 2040 and likely requires net emissions to become zero or possibly negative later in the century. Accounting for the temperature effects of non-CO_2 species, cumulative CO_2 emissions are required to stay below about 800 GtC in order to provide a two-thirds likelihood of preventing 3.6°F (2°C) of warming, meaning approximately 230 GtC more could be emitted globally. Assuming global emissions follow the range between the RCP8.5 and RCP4.5 scenarios, emissions could continue for approximately two decades before this cumulative carbon threshold is exceeded. (Ch.14)

- Successful implementation of the first round of Nationally Determined Contributions associated with the Paris Agreement will provide some likelihood of meeting the long-term temperature goal of limiting global warming to "well below" 3.6°F (2°C) above preindustrial levels; the likelihood depends strongly on the magnitude of global emission reductions after 2030. (*High confidence*) (Ch.14)

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- Climate intervention or geoengineering strategies such as solar radiation management are measures that attempt to limit or reduce global temperature increases. If interest in geoengineering increases with observed impacts and/or projected risks of climate change, interest will also increase in assessments of the technical feasibilities, costs, risks, co-benefits, and governance challenges of these additional measures, which are as yet unproven at scale. These assessments are a necessary step before judgments about the benefits and risks of these approaches can be made with high confidence. (*High confidence*) (Ch.14)

- As a whole, the terrestrial biosphere (soil and plants) is a net "sink" for carbon (drawing down carbon from the atmosphere), and this sink has steadily increased since 1980 (*very high confidence*). Because of the uncertainty in the trajectory of land cover, the possibility of the land becoming a net carbon source cannot be excluded (*very high confidence*). (Ch.10)

There is a Significant Possibility for Unanticipated Changes

Humanity is conducting an unprecedented experiment with the Earth's climate system through emissions from large-scale fossil-fuel combustion, widespread deforestation, and other changes to the atmosphere and landscape. While researchers and policymakers must rely on climate model projections for a representative picture of the future Earth system under these conditions, there are still elements of the Earth system that models do not capture well. For this reason, there is significant potential for humankind's planetary experiment to result in unanticipated surprises—and the further and faster the Earth's climate system is changed, the greater the risk of such surprises.

There are at least two types of potential surprises: *compound events*, where multiple extreme climate events occur simultaneously or sequentially (creating greater overall impact), and *critical threshold* or *tipping point events*, where some threshold is crossed in the climate system (that leads to large impacts). The probability of such surprises – some of which may be abrupt and/or irreversible - as well as other more predictable but difficult-to-manage impacts, increases as the influence of human activities on the climate system increases. (Ch.15)

Unanticipated and difficult or impossible-to-manage changes in the climate system are possible throughout the next century as critical thresholds are crossed and/or multiple climate-related extreme events occur simultaneously. (Ch.15)

- Positive feedbacks (self-reinforcing cycles) within the climate system have the potential to accelerate human-induced climate change and even shift the Earth's climate system, in part or in whole, into new states that are very different from those experienced in the recent past (for example, ones with greatly diminished ice sheets or

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different large-scale patterns of atmosphere or ocean circulation). Some feedbacks and potential state shifts can be modeled and quantified; others can be modeled or identified but not quantified; and some are probably still unknown. (*Very high confidence* in the potential for state shifts and in the incompleteness of knowledge about feedbacks and potential state shifts). (Ch.15)

- The physical and socioeconomic impacts of compound extreme events (such as simultaneous heat and drought, wildfires associated with hot and dry conditions, or flooding associated with high precipitation on top of snow or waterlogged ground) can be greater than the sum of the parts *(very high confidence)*. Few analyses consider the spatial or temporal correlation between extreme events. (Ch.15)

- While climate models incorporate important climate processes that can be well quantified, they do not include all of the processes that can contribute to feedbacks (Ch. 2), compound extreme events, and abrupt and/or irreversible changes. For this reason, future changes outside the range projected by climate models cannot be ruled out (*very high confidence*). Moreover, the systematic tendency of climate models to underestimate temperature change during warm paleoclimates suggests that climate models are more likely to underestimate than to overestimate the amount of long-term future change (*medium confidence*). (Ch.15)

******BOX ES.2*******

A Summary of Advances Since NCA3

Advances in scientific understanding and scientific approach, as well as developments in global policy, have occurred since NCA3. A detailed summary of these advances can be found at the end of Chapter 1: Our Globally Changing Climate. Highlights of what aspects are either especially strengthened or are emerging in the current findings include:

- *Detection and attribution*: Significant advances have been made in the attribution of the human influence for individual climate and weather extreme events since NCA3. (Chapters 3,6,7,8).

- *Atmospheric circulation and extreme events*: The extent to which atmospheric circulation in the midlatitudes is changing or is projected to change, possibly in ways not captured by current climate models, is a new important area of research. (Chapters 5,6,7).

- *Increased understanding of specific types of extreme events*: How climate change may affect specific types of extreme events in the United States is another key area where scientific understanding has advanced. (Chapter 9).

- *High-resolution global climate model simulations*: As computing resources have grown, multidecadal simulations of global climate models are now being conducted at horizontal resolutions on the order of 15 miles (25 km) that provide more realistic

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characterization of intense weather systems, including hurricanes. (Chapter 9).

- *Oceans and coastal waters*: Concern over ocean acidification, warming, and oxygen loss is increasing as scientific understanding of the severity of their impacts grows. Both oxygen loss and acidification may be magnified in some U.S. coastal waters relative to the global average, raising the risk of serious ecological and economic consequences. (Chapters 2, 13).

- *Local sea level change projections*: For the first time in the NCA process, sea level rise projections incorporate geographic variation based on factors such as local land subsidence, ocean currents, and changes in Earth's gravitational field. (Chapter 12).

- *Accelerated ice-sheet loss and irreversibility*: New observations from many different sources confirm that ice-sheet loss is accelerating. Combining observations with simultaneous advances in the physical understanding of ice sheets, leads to the conclusion that up to 8.5 feet of global sea level rise is possible by 2100 under a high emissions scenario (RCP8.5), up from 6.6 feet in NCA3. (Chapter 12).

- *Slower regrowth in Arctic sea ice area extent in fall and winter 2016–2017*: The annual Arctic sea ice extent minimum for 2016 relative to the long-term record was the second lowest on record; since 1981, the sea ice minimum has decreased by 13.3% per decade, more than 46% over the 35 years. In fall and winter 2016–2017, record-setting slow seasonal ice regrowth was the lowest since observations began in 1981. (Chapter 11).

- *Potential surprises*: Both large-scale state shifts in the climate system (sometimes called "tipping points") and compound extremes have the potential to generate unanticipated climate surprises. The further the Earth system departs from historical climate forcings, and the more the climate changes, the greater the potential for these surprises. (Chapter 15).

- *The Paris Agreement*: The Paris Agreement, which entered into force in 2016, provides a new framework for its parties for the mitigation of and adaption to climate change. This report discusses some important aspects of climate science that are relevant to the Agreement. (Chapters 4, 14).

******End Box ES.2******

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1. Our Globally Changing Climate

KEY FINDINGS

1. The global climate continues to change rapidly compared to the pace of the natural variations in climate that have occurred throughout Earth's history. Trends in globally averaged temperature, sea level rise, upper-ocean heat content, land-based ice melt, Arctic sea ice, depth of seasonal permafrost thaw, and other climate variables provide consistent evidence of a warming planet. These observed trends are robust and have been confirmed by multiple independent research groups around the world. (*Very high confidence*)

2. The frequency and intensity of extreme heat and heavy precipitation events are increasing in most continental regions of the world (*very high confidence*). These trends are consistent with expected physical responses to a warming climate. Climate model studies are also consistent with these trends, although models tend to underestimate the observed trends, especially for the increase in extreme precipitation events (*very high confidence* for temperature, *high confidence* for extreme precipitation). The frequency and intensity of extreme temperature events are *virtually certain* to increase in the future as global temperature increases (*high confidence*). Extreme precipitation events will *very likely* continue to increase in frequency and intensity throughout most of the world (*high confidence*). Observed and projected trends for some other types of extreme events, such as floods, droughts, and severe storms, have more variable regional characteristics.

3. Many lines of evidence demonstrate that it is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century. Formal detection and attribution studies for the period 1951 to 2010 find that the observed global mean surface temperature warming lies in the middle of the range of likely human contributions to warming over that same period. We find no convincing evidence that natural variability can account for the amount of global warming observed over the industrial era. For the period extending over the last century, there are no convincing alternative explanations supported by the extent of the observational evidence. Solar output changes and internal variability can only contribute marginally to the observed changes in climate over the last century, and we find no convincing evidence for natural cycles in the observational record that could explain the observed changes in climate. (*Very high confidence*)

4. Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades will depend primarily on the amount of greenhouse (heat-trapping) gases emitted globally and on the remaining uncertainty in the sensitivity of Earth's climate to those emissions (very *high confidence)*. With significant reductions in the emissions of greenhouse gases, the global annually

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averaged temperature rise could be limited to 3.6°F (2°C) or less. Without major reductions in these emissions, the increase in annual average global temperatures relative to preindustrial times could reach 9°F (5°C) or more by the end of this century (*high confidence*).

5. Natural variability, including El Niño events and other recurring patterns of ocean–atmosphere interactions, impact temperature and precipitation, especially regionally, over months to years. The global influence of natural variability, however, is limited to a small fraction of observed climate trends over decades. (*Very high confidence*)

6. Longer-term climate records over past centuries and millennia indicate that average temperatures in recent decades over much of the world have been much higher, and have risen faster during this time period, than at any time in the past 1,700 years or more, the time period for which the global distribution of surface temperatures can be reconstructed. (*High confidence*)

1.1. Introduction

Since the Third U.S. National Climate Assessment (NCA3) was published in May 2014, new observations along multiple lines of evidence have strengthened the conclusion that Earth's climate is changing at a pace and in a pattern not explainable by natural influences. While this report focuses especially on observed and projected future changes for the United States, it is important to understand those changes in the global context (this chapter).

The world has warmed over the last 150 years, especially over the last six decades, and that warming has triggered many other changes to Earth's climate. Evidence for a changing climate abounds, from the top of the atmosphere to the depths of the oceans. Thousands of studies conducted by tens of thousands of scientists around the world have documented changes in surface, atmospheric, and oceanic temperatures; melting glaciers; disappearing snow cover; shrinking sea ice; rising sea level; and an increase in atmospheric water vapor. Rainfall patterns and storms are changing and the occurrence of droughts is shifting.

Many lines of evidence demonstrate that human activities, especially emissions of greenhouse gases, are primarily responsible for the observed climate changes in the industrial era, especially over the last six decades (see attribution analysis in Ch. 3: Detection and Attribution). Formal detection and attribution studies for the period 1951 to 2010 find that the observed global mean surface temperature warming lies in the middle of the range of likely human contributions to warming over that same period. The Intergovernmental Panel on Climate Change concluded that it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century (IPCC 2013). Over the last century, there are no alternative explanations supported by the evidence that are either credible or that can contribute more than marginally to the observed patterns. We find no convincing evidence that natural variability can

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account for the amount of global warming observed over the industrial era. Solar flux variations over the last six decades have been too small to explain the observed changes in climate (Bindoff et al. 2013). There are no apparent natural cycles in the observational record that can explain the recent changes in climate (e.g., PAGES 2K Consortium 2013; Marcott et al. 2013). In addition, natural cycles within the Earth's climate system can only redistribute heat; they cannot be responsible for the observed increase in the overall heat content of the climate system (Church et al. 2011). Any explanations for the observed changes in climate must be grounded in understood physical mechanisms, appropriate in scale, and consistent in timing and direction with the long-term observed trends. Known human activities quite reasonably explain what has happened without the need for other factors. Internal variability and forcing factors other than human activities cannot explain what is happening and there are no suggested factors, even speculative ones, that can explain the timing or magnitude and that would somehow cancel out the role of human factors (Anderson et al. 2012). The science underlying this evidence, along with the observed and projected changes in climate, is discussed in later chapters, starting with the basis for a human influence on climate in Chapter 2: Physical Drivers of Climate Change.

Throughout this report, we also analyze projections of future changes in climate. Predicting how climate will change in future decades is a different scientific issue from predicting weather a few weeks from now. Local weather is short term, with limited predictability, and is determined by the complicated movement and interaction of high pressure and low pressure systems in the atmosphere; thus, it is difficult to forecast day-to-day changes beyond about two weeks into the future. Climate, on the other hand, is the statistics of weather—meaning not just average values but also the prevalence and intensity of extremes—as observed over a period of decades. Climate emerges from the interaction, over time, of rapidly changing local weather and more slowly changing regional and global influences, such as the distribution of heat in the oceans, the amount of energy reaching Earth from the sun, and the composition of the atmosphere. See Chapter 4: Projections and later chapters for more on climate projections.

Throughout this report, we include many findings that further strengthen or add to the understanding of climate change relative to those found in NCA3 and other assessments of the science. Several of these are highlighted in an "Advances Since NCA3" box at the end of this chapter.

1.2. Indicators of a Globally Changing Climate

Highly diverse types of direct measurements made on land, sea, and in the atmosphere over many decades have allowed scientists to conclude with high confidence that global mean temperature is increasing. Observational datasets for many other climate variables support the conclusion with high confidence that the global climate is changing (Blunden and Arndt 2016; Meehl et al. 2016a; also see EPA 2016). Figure 1.1 depicts several of the observational indicators that demonstrate trends consistent with a warming planet over the last century. Temperatures in the lower atmosphere and ocean have increased, as have near-surface humidity and sea level. Not

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only has ocean heat content increased dramatically (Figure 1.1), but more than 90% of the energy gained in the combined ocean–atmosphere system over recent decades has gone into the ocean (Rhein et al. 2013; Johnson et al. 2015).

Basic physics tells us that a warmer atmosphere can hold more water vapor; this is exactly what is measured from satellite data. At the same time, a warmer world means higher evaporation rates and major changes to the hydrological cycle, including increases in the prevalence of torrential downpours. In addition, Arctic sea ice, mountain glaciers, and Northern Hemisphere spring snow cover have all decreased. The relatively small increase in Antarctic sea ice in the 15-year period from 2000 through early 2016 appears to be best explained as being due to localized natural variability (see e.g., Meehl et al. 2016a; Ramsayer 2014); while possibly also related to natural variability, the 2017 Antarctic sea ice minimum reached in early March was the lowest measured since reliable records began in 1979. The vast majority of the glaciers in the world are losing mass at significant rates. The two largest ice sheets on our planet—on the land masses of Greenland and Antarctica—are shrinking. Five different observational datasets show the heat content of the oceans is increasing.

Many other indicators of the changing climate have been determined from other observations – for example, changes in the growing season and the allergy season (see e.g., EPA 2016; USGCRP 2017). In general, the indicators demonstrate continuing changes in climate since the publication of NCA3. As with temperature, independent researchers have analyzed each of these indicators and come to the same conclusion: all of these changes paint a consistent and compelling picture of a warming planet.

[INSERT FIGURE 1.1 HERE]

1.3. Trends in Global Temperatures

Global annual-average temperature (as calculated from instrumental records over both land and oceans; used interchangeably with global average temperature in the discussion below) has increased by more than 1.2°F (0.7°C) for the period 1986–2016 relative to 1901–1960 (Figure 1.2); see Vose et al. (2012) for discussion on how global annual-average temperature is derived by scientists. The linear regression change over the entire period from 1901–2016 is 1.8°F (1.0°C). Global average temperature is not expected to increase smoothly over time in response to the human warming influences, because the warming trend is superimposed on natural variability associated with, for example, the El Niño/ La Niña ocean-heat oscillations and the cooling effects of particles emitted by volcanic eruptions. Even so, 16 of the 17 warmest years in the instrumental record (since the late 1800s) occurred in the period from 2001 to 2016 (1998 was the exception). Global average temperature for 2016 has now surpassed 2015 by a small amount as the warmest year on record. The year 2015 far surpassed 2014 by 0.29°F (0.16°C), four times greater than the difference between 2014 and the next warmest year, 2010 (NCEI

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2016). Three of the four warmest years on record have occurred since the analyses through 2012 were reported in NCA3.

A strong El Niño contributed to 2015's record warmth (Blunden and Arndt 2016). Though an even more powerful El Niño occurred in 1998, the global temperature in that year was significantly lower (by 0.49°F [0.27°C]) than that in 2015. This suggests that human-induced warming now has a stronger influence on the occurrence of record temperatures than El Niño events. In addition, the El Niño/La Niña cycle may itself be affected by the human influence on the Earth's climate system (Steinman et al. 2012; Trenberth 2015). It is the complex interaction of natural sources of variability with the continuously growing human warming influence that is now shaping the Earth's weather and, as a result, its climate.

Globally, the persistence of the warming over the past 60 years far exceeds what can be accounted for by natural variability alone (IPCC 2013). That does not mean, of course, that natural sources of variability have become insignificant. They can be expected to continue to contribute a degree of "bumpiness" in the year-to-year global average temperature trajectory, as well as exert influences on the average rate of warming that can last a decade or more (Deser et al. 2012; Karl et al. 2015; Knutson et al. 2016) (see Box 1.1).

[INSERT FIGURE 1.2 HERE]

Warming during the first half of the 1900s occurred mostly in the Northern Hemisphere (Delworth and Knutson 2000). Recent decades have seen greater warming in response to accelerating increases in greenhouse gas concentrations, particularly at high northern latitudes, and over land as compared to the ocean (see Figure 1.3). In general, winter is warming faster than summer (especially in northern latitudes). Also, nights are warming faster than days (Alexander et al. 2006; Davy et al. 2016). There is also some evidence of faster warming at higher elevations (Mountain Research Initiative 2015).

Most ocean areas around the Earth are warming (see Ch. 13: Ocean Changes). Even in the absence of significant ice melt, the ocean is expected to warm more slowly given its larger heat capacity, leading to land–ocean differences in warming (as seen in Figure 1.3). As a result, the climate for land areas often responds more rapidly than the ocean areas, even though the forcing driving a change in climate occurs equally over land and the oceans (IPCC 2013). A few regions, such as the North Atlantic Ocean, have experienced cooling over the last century, though these areas have warmed over recent decades. Regional climate variability is important (e.g., Hurrell and Deser 2009; Hoegh-Guldberg et al. 2014) as are the effects of the increasing freshwater in the North Atlantic from melting of sea and land ice (Rahmstorf et al. 2015).

[INSERT FIGURE 1.3 HERE]

Figure 1.4 shows the projected changes in globally averaged temperature for a range of future pathways that vary from assuming strong continued dependence on fossil fuels in energy and

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transportation systems over the 21st century (the high scenario is Representative Concentration Pathway 8.5, or RCP8.5) to assuming major emissions-reduction actions (the very low scenario, RCP2.6). Chapter 4: Projections describes the future scenarios and the models of Earth's climate system being used to quantify the impact of human choices and natural variability on future climate. These analyses also suggest that global surface temperature increases for the end of the 21st century are *very likely* to exceed 1.5°C (2.7°F) relative to the 1850–1900 average for all projections, with the exception of the lowest part of the uncertainty range for RCP2.6 (IPCC 2013).

[INSERT FIGURE 1.4 HERE]

----- START BOX 1.1 HERE -----

Box 1.1. Was there a "Hiatus" in Global Warming?

Natural variability in the climate system leads to year-to-year and decade-to-decade changes in global mean temperature. For short enough periods of time, this variability can lead to temporary slowdowns or even reversals in the globally-averaged temperature increase. Over the past decade, such a slowdown led to numerous assertions about a 'hiatus' (a period of zero or negative temperature trend) in global warming. For longer periods, variability becomes less important, and the long-term increase in global temperature is clearly revealed in both the surface temperature data and in satellite measurements of tropospheric temperature (see Figure 1.5) (Santer et al. 2017a). Thus the surface and tropospheric temperature records do not support the assertion that long-term (time periods of 25 years or longer) global warming has ceased or substantially slowed (Lewandowsky et al. 2016; Santer et al. 2017b), a conclusion further reinforced by recently updated and improved datasets (Karl et al. 2015; Mears and Wentz 2016; Richardson et al. 2016; Hausfather et al. 2017).

[INSERT FIGURE 1.5 HERE]

For the 15 years following the 1997–1998 El Niño–Southern Oscillation (ENSO) event, the observed rate of temperature increase was smaller than the underlying long-term increasing trend on 30-year climate time scales (Fyfe et al. 2016), even as other measures of global warming such as ocean heat content (see Ch. 13: Ocean Changes) and Arctic sea ice extent (see Ch. 12: Sea Level Rise) continued to change (Benestad 2017). Variation in the rate of warming on this time scale is not unexpected and can be the result of long-term internal variability in the climate system, or short-term changes in climate forcings such as aerosols or solar irradiance. Temporary periods similar or larger in magnitude to the current slowdown have occurred earlier in the historical record (in addition, almost no increase occurred from the mid 1940s to the mid 1970s, which is not well understood but may be related to an increase in anthropogenic and volcanic aerosols and/or to ocean interactions (Meehl et al. 2016a)) during this period. Shorter-term slowdowns also occur after major volcanic eruptions, such as Pinatubo's eruption in 1991.

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Temporary speedups have also occurred, most notably in the 1930s and early 1940s, and in the late 1970s and early 1980s. Comparable slowdown and speedup events are also present in climate simulations of both historical and future climate, even without decadal scale fluctuations in forcing (Easterling and Wehner 2009; Knutson et al. 2016), and thus recent variations in short-term temperature trend statistics are not particularly surprising.

Even though such slowdowns are not unexpected, the slowdown of the early 2000s has been used as informal evidence to cast doubt on the accuracy of climate projections from CMIP5 models, since the measured rate of warming in all surface and tropospheric temperature datasets from 2000 to 2014 was less than was expected given the results of the CMIP3 and CMIP5 historical climate simulations (Fyfe et al. 2016; Santer et al. 2017a). Thus, it is important to explore a physical explanation of the recent slowdown and to identify the relative contributions of different factors.

Numerous studies have investigated the role of natural modes of variability and how they affected the flow of energy in the climate system of the post-2000 period (Balmaseda et al. 2013; England et al. 2014; Meehl et al. 2011; Kosaka and Xie 2013; Meehl et al. 2016a). For the 2000–2013 time period, they find

- In the Pacific Ocean, a number of interrelated features, including cooler than expected tropical ocean surface temperatures, stronger than normal trade winds, and a shift to the cool phase of the Pacific Decadal Oscillation (PDO) led to cooler than expected surface temperatures in the Eastern Tropical Pacific, a region that has been shown to have an influence on global-scale climate (Kosaka and Xie 2013).

- For most of the world's oceans, heat was transferred from the surface into the deeper ocean (Balmaseda et al. 2013; Chen and Tung 2014; Nieves et al. 2015), causing a reduction in surface warming worldwide.

- Other studies attributed part of the cause of the measurement/model discrepancy to natural fluctuations in radiative forcings, such as volcanic aerosols, stratospheric water vapor, or solar output (Solomon et al. 2010; Schmidt et al 2014; Huber and Knutti 2014; Ridley et al. 2014; Santer et al. 2014).

When comparing model predictions with measurements, it is important to note that the CMIP5 runs used an assumed representation of these factors for time periods after 2000, possibly leading to errors, especially in the year-to-year simulation of internal variability in the oceans. It is *very likely* that the early 2000s slowdown was caused by a combination of short-term variations in forcing and internal variability in the climate system, though the relative contribution of each is still an area of active research (e.g., Trenberth 2015; Meehl et al. 2016a; Fyfe et al. 2016).

Although 2014 already set a new high in globally averaged temperature record up to that time, in 2015–2016, the situation changed dramatically. A switch of the PDO to the positive phase,

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combined with a strong El Niño event during the fall and winter of 2015–2016, led to months of record-breaking globally averaged temperatures in both the surface and satellite temperature records (see Figure 1.5; Trenberth 2015), bringing observed temperature trends into better agreement with model expectations (see Figure 1.6).

On longer time scales, observed temperature changes are more consistent with model simulations and have been attributed to anthropogenic causes with high confidence (Bindoff et al. 2013; see Ch. 3: Detection and Attribution for further discussion). The pronounced globally averaged surface temperature record of 2015 and 2016 appear to make recent observed temperature changes more consistent with model simulations—including with CMIP5 projections that were (notably) developed in advance of occurrence of the 2015–2016 observed anomalies (Figure 1.6). A second important point illustrated by Figure 1.6 is the broad overall agreement between observations and models on the century timescale, which is robust to the shorter-term variations in trends in the past decade or so. Continued global warming and the frequent setting of new high global mean temperature records or near-records is consistent with expectations based on model projections of continued anthropogenic forcing toward warmer global mean conditions.

[INSERT FIGURE 1.6 HERE]

----- END BOX 1.1 HERE -----

1.4. Trends in Global Precipitation

Annual averaged precipitation across global land areas exhibits a slight rise (that is not statistically significant because of a lack of data coverage early in the record) over the past century (see Figure 1.7) along with ongoing increases in atmospheric moisture levels. Interannual and interdecadal variability is clearly found in all precipitation evaluations, owing to factors such as the North Atlantic Oscillation (NAO) and ENSO—note that precipitation reconstructions are updated operationally by NOAA NCEI on a monthly basis (Becker et al. 2013; Adler et al. 2003).

[INSERT FIGURE 1.7 HERE]

The hydrological cycle and the amount of global mean precipitation is primarily controlled by the atmosphere's energy budget and its interactions with clouds (Allen and Ingram 2002). The amount of global mean precipitation also changes as a result of a mix of fast and slow atmospheric responses to the changing climate (Collins et al. 2013). In the long term, increases in tropospheric radiative effects from increasing amounts of atmospheric CO_2 (i.e., increasing CO_2 leads to greater energy absorbed by the atmosphere and re-emitted to the surface, with the additional transport to the atmosphere coming by convection) must be balanced by increased latent heating, resulting in precipitation increases of approximately 0.55% to 0.72% per °F (1% to 3% per °C) (IPCC 2013; Held and Soden 2006). Global atmospheric water vapor should increase by about 6%–7% per °C of warming based on the Clausius–Clapeyron relationship (see

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Ch. 2: Physical Drivers of Climate Change); satellite observations of changes in precipitable water over oceans have been detected at about this rate and attributed to human-caused changes in the atmosphere (Santer et al. 2007). Similar observed changes in land-based measurements have also been attributed to the changes in climate from greenhouse gases (Willet et al. 2010).

Earlier studies suggested a climate change pattern of wet areas getting wetter and dry areas getting drier (e.g., Greve et al. 2014). While Hadley Cell expansion should lead to more drying in the subtropics, the poleward shift of storm tracks should lead to enhanced wet regions. While this high/low rainfall behavior appears to be valid over ocean areas, changes over land are more complicated. The wet versus dry pattern in observed precipitation has only been attributed for the zonal mean (Zhang et al. 2007; Marvel and Bonfils 2013) and not regionally due to the large amount of spatial variation in precipitation changes as well as significant natural variability. The detected signal in zonal mean precipitation is largest in the Northern Hemisphere, with decreases in the subtropics and increases at high latitudes. As a result, the observed increase (about 5% since the 1950s [Walsh et al. 2011; Vihma et al. 2016]) in annual averaged Arctic precipitation have been detected and attributed to human activities (Min et al. 2008).

1.5. Trends in Global Extreme Weather Events

A change in the frequency, duration, and/or magnitude of extreme weather events is one of the most important consequences of a warming climate. In statistical terms, a small shift in the mean of a weather variable, with or without this shift occurring in concert with a change in the shape of its probability distribution, can cause a large change in the probability of a value relative to an extreme threshold (Katz and Brown 1992; see Figure 1.8 in IPCC 2013). Examples include extreme high temperature events and heavy precipitation events. Additionally, extreme events such as intense tropical cyclones, midlatitude cyclones, and hail and tornadoes associated with thunderstorms can occur as isolated events that are not generally studied in terms of extremes within a probability distribution. Detecting trends in the frequency and intensity of extreme weather events is challenging (Sardeshmukh et al. 2015). The most intense events are rare by definition, and observations may be incomplete and suffer from reporting biases. Further discussion on trends and projections of extreme events for the United States can be found in Chapters 6–9 and 11.

An emerging area in the science of detection and attribution has been the attribution of extreme weather and climate events. Extreme event attribution generally addresses the question of whether climate change has altered the odds of occurrence of an extreme event like one just experienced. Attribution of extreme weather events under a changing climate is now an important and highly visible aspect of climate science. As discussed in a recent National Academy of Sciences (NAS) report (NAS 2016), the science of event attribution is rapidly advancing, including the understanding of the mechanisms that produce extreme events and the development of methods that are used for event attribution. Several other reports and papers have reviewed the topic of extreme event attribution (Hulme 2014; Stott 2016; Easterling et al. 2016).

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