2 Our Changing Climate

Federal Coordinating Lead Authors

David R. Easterling
NOAA National Centers for Environmental Information

David W. Fahey
NOAA Earth System Research Laboratory

Chapter Lead

Katharine Hayhoe
Texas Tech University

Chapter Authors

Sarah Doherty
University of Washington

James P. Kossin
NOAA National Centers for Environmental Information

William V. Sweet
NOAA National Ocean Service

Russell S. Vose
NOAA National Centers for Environmental Information

Michael F. Wehner
Lawrence Berkeley National Laboratory

Donald J. Wuebbles
University of Illinois

Review Editor

Linda O. Mearns
National Center for Atmospheric Research

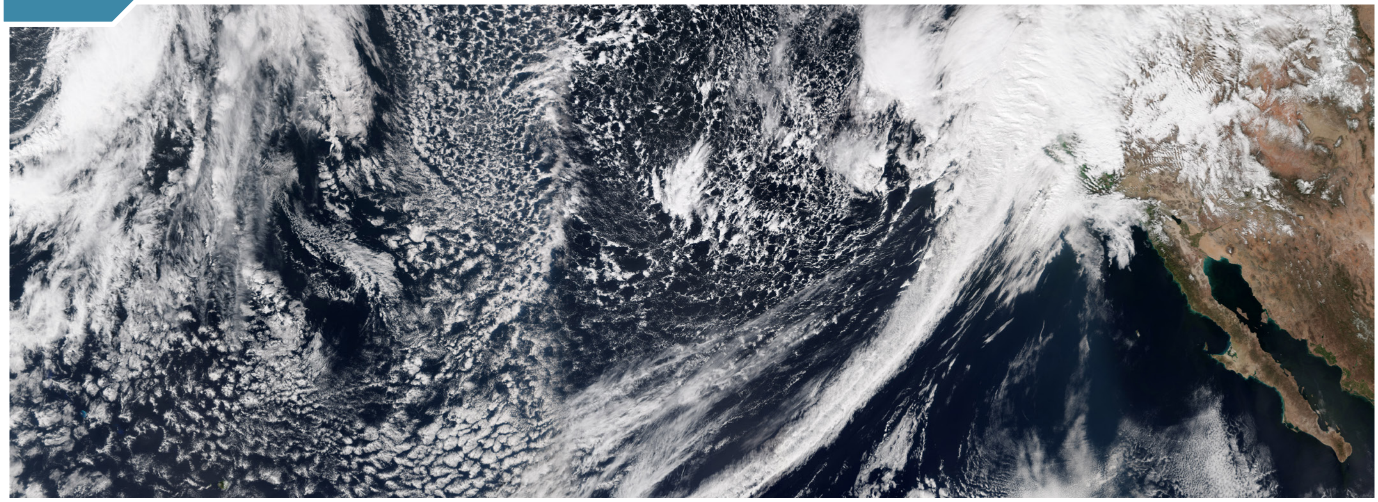
Technical Contributors are listed at the end of the chapter.

Recommended Citation for Chapter

Hayhoe, K., D.J. Wuebbles, D.R. Easterling, D.W. Fahey, S. Doherty, J. Kossin, W. Sweet, R. Vose, and M. Wehner, 2018: Our Changing Climate. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 72–144. doi: 10.7930/NCA4.2018.CH2

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

2 Our Changing Climate



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

Key Message 1

Observed Changes in Global Climate

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

Key Message 2

Future Changes in Global Climate

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

Key Message 3

Warming and Acidifying Oceans

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

Key Message 4

Rising Global Sea Levels

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

Key Message 5

Increasing U.S. Temperatures

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

Key Message 6

Changing U.S. Precipitation

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

Key Message 7

Rapid Arctic Change

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

Key Message 8

Changes in Severe Storms

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

Key Message 9

Increases in Coastal Flooding

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

Key Message 10

Long-Term Changes

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

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

Key Message 1

Observed Changes in Global Climate

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

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

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

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

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

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

Box 2.1: Natural Variability

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

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

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

Box 2.2: Indicators

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

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

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

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

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

Human and Natural Influences on Global Temperature

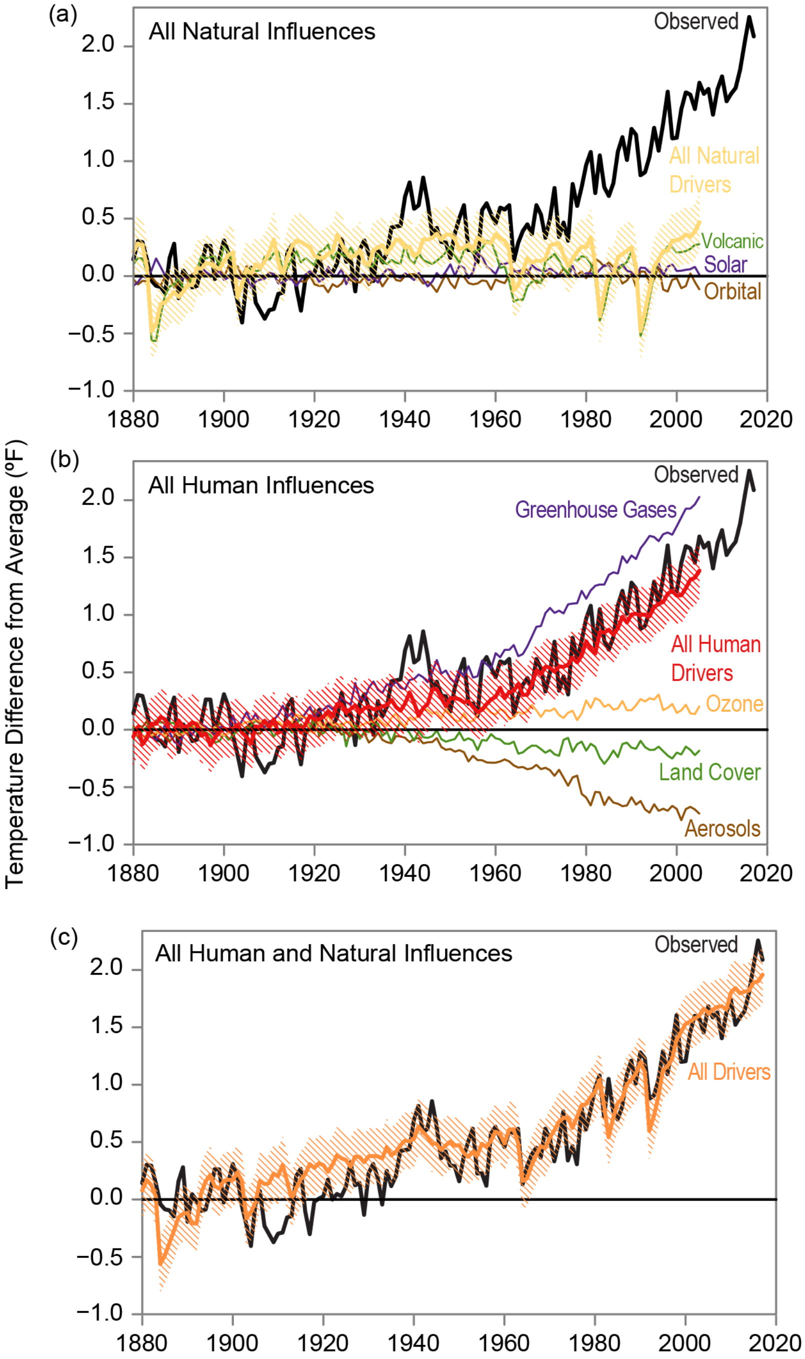


Figure 2.1: Both human and natural factors influence Earth's climate, but the long-term global warming trend observed over the past century can only be explained by the effect that human activities have had on the climate.

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

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

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

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

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

Key Message 2

Future Changes in Global Climate

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

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

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

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

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

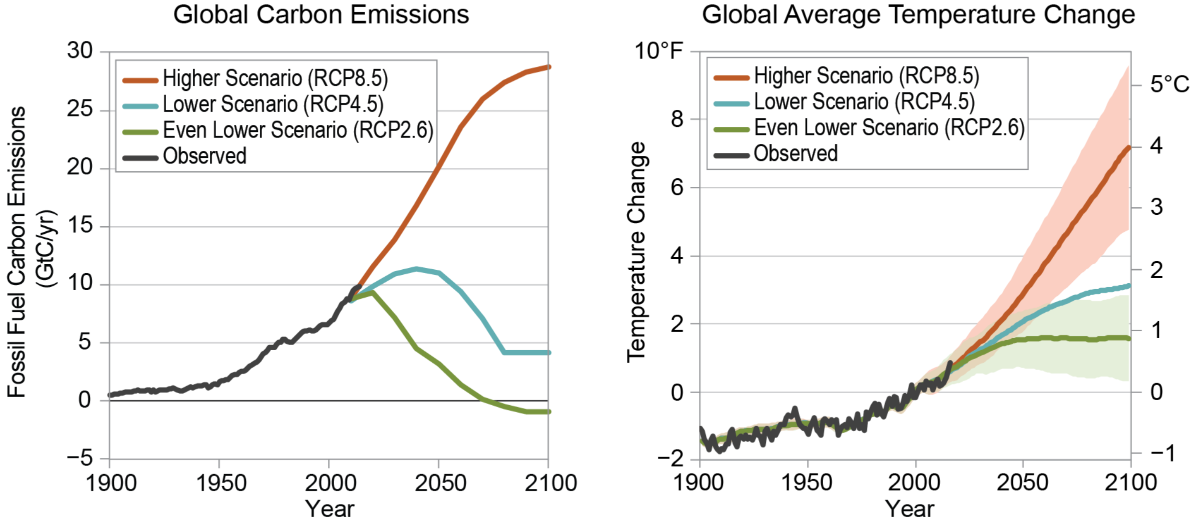
Periodically taking stock of the current state of knowledge about climate change and putting new weather extremes, changes in sea ice, increases in ocean temperatures, and ocean acidification into context ensures that rigorous, scientific-based information is available to inform dialog and decisions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

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

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

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

Observed and Projected Changes in Carbon Emissions and Temperature


Global Carbon Emissions

Global Average Temperature Change

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

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

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

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

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

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

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

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

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

Key Message 3

Warming and Acidifying Oceans

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

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

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

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

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

Key Message 4

Rising Global Sea Levels

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

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

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

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

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

Historical and Projected Global Average Sea Level Rise

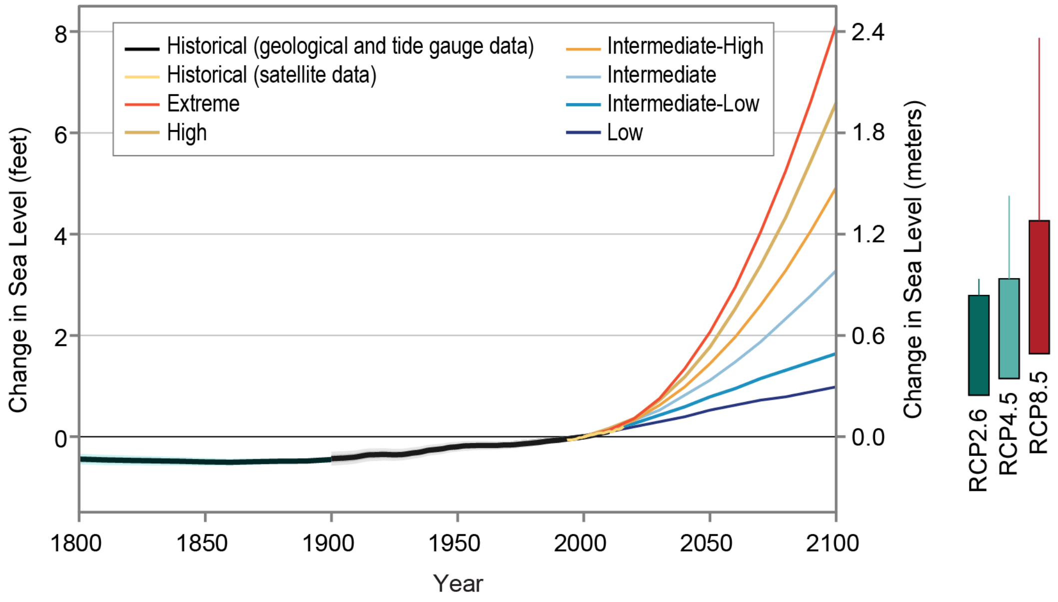


Figure 2.3. How much global average sea level will rise over the rest of this century depends on the response of the climate system to warming, as well as on future scenarios of human-caused emissions of heat-trapping gases. The colored lines show the six different global average sea level rise scenarios, relative to the year 2000, that were developed by the U.S. Federal Interagency Sea Level Rise Taskforce[76] to describe the range of future possible rise this century. The boxes on the right-hand side show the *very likely* ranges in sea level rise by 2100, relative to 2000, corresponding to the different RCP scenarios described in Figure 2.2. The lines above the boxes show possible increases based on the newest research of the potential Antarctic contribution to sea level rise (for example, DeConto and Pollard 2016[80] versus Kopp et al. 2014[77]). Regardless of the scenario followed, it is *extremely likely* that global average sea level rise will continue beyond 2100. Source: adapted from Sweet et al. 2017.[57] *This figure was revised in June 2019. See Errata for details: https://nca2018.globalchange.gov/downloads*

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

Key Message 5

Increasing U.S. Temperatures

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

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

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

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

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

Observed and Projected Changes in Annual Average Temperature

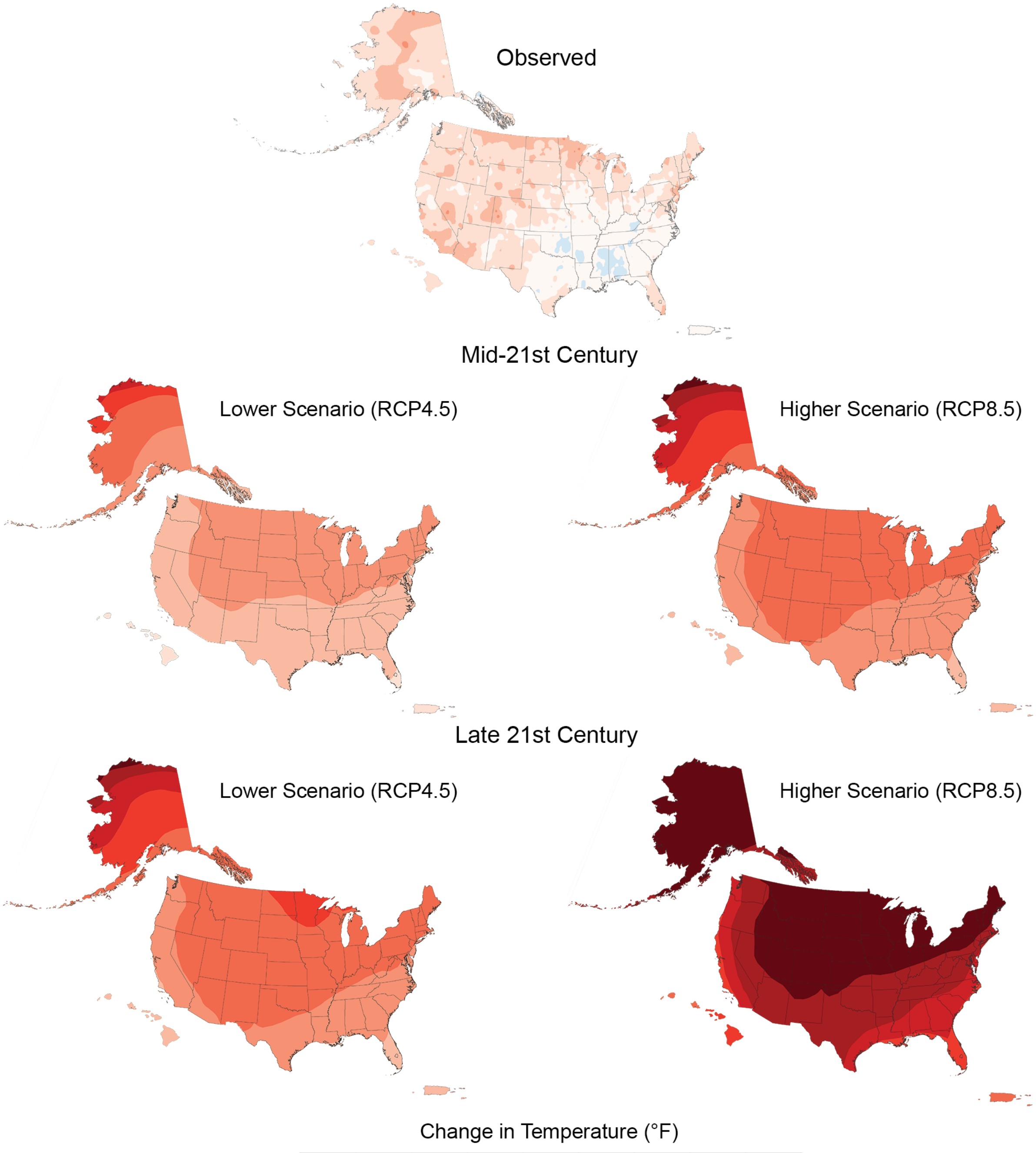


Figure 2.4: Annual average temperatures across North America are projected to increase, with proportionally greater changes at higher as compared to lower latitudes, and under a higher scenario (RCP8.5, right) as compared to a lower one (RCP4.5, left). This figure compares (top) observed change for 1986–2016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

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

Key Message 6

Changing U.S. Precipitation

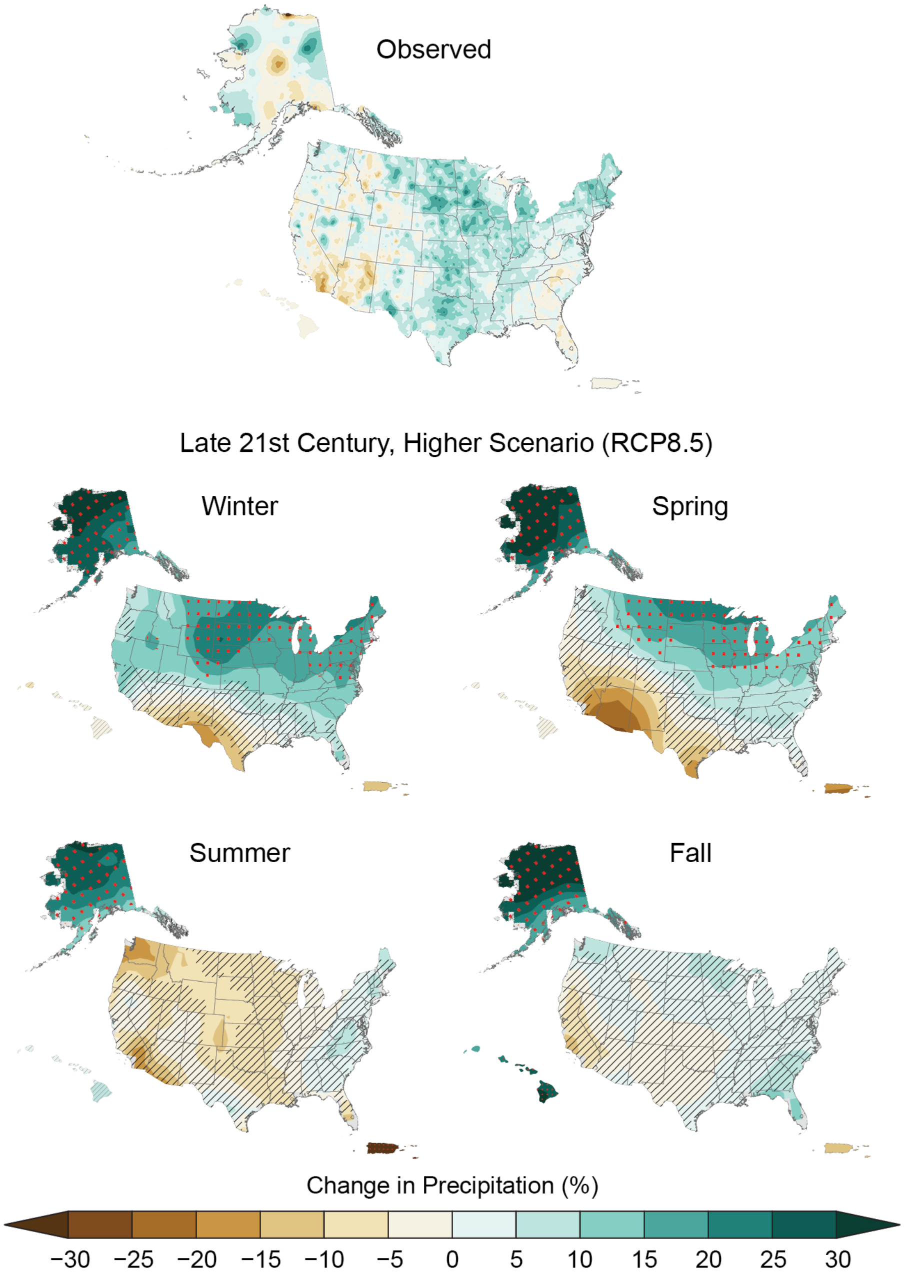
Annual precipitation since the beginning of the last century has increased across most of the northern and eastern United States and decreased across much of the southern and western United States. Over the coming century, significant increases are projected in winter and spring over the Northern Great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

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

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

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

Observed and Projected Change in Seasonal Precipitation



Observed

Late 21st Century, Higher Scenario (RCP8.5)

Winter

Spring

Summer

Fall

Change in Precipitation (%)

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

Observed and Projected Change in Heavy Precipitation

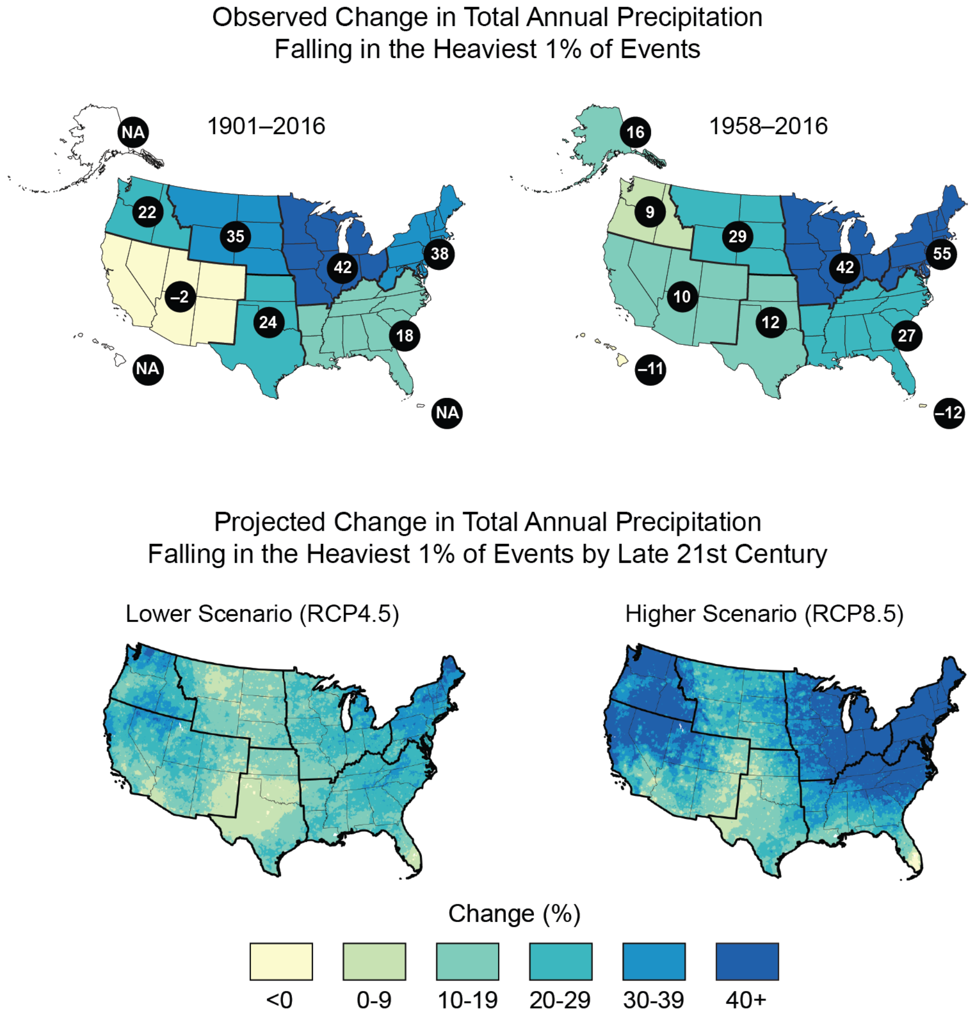


Figure 2.6: Heavy precipitation is becoming more intense and more frequent across most of the United States, particularly in the Northeast and Midwest, and these trends are projected to continue in the future. This map shows the observed (top; numbers in black circles give the percentage change) and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

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

Declines have been observed in North America spring snow cover extent and maximum snow depth, as well as snow water equivalent (a measurement of the amount of water stored in snowpack) in the western United States and extreme snowfall years in the southern and western United States.[102,103,104] All are consistent with observed warming, and of these trends, human-induced warming has been formally identified as a factor in earlier spring melt and reduced snow water equivalent.[101] Projections show large declines in snowpack in the western United States and shifts to more precipitation falling as rain rather than snow in many parts of the central and eastern United States. Under higher future scenarios, assuming no change to current water resources management, snow-dominated watersheds in the western United States are more likely to experience lengthy and chronic hydrological drought conditions by the end of this century.[105,106,107]

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

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

Key Message 7

Rapid Arctic Change

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

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

Some of the most rapid observed changes are occurring in Alaska and across the Arctic. Over the last 50 years, for example, annual average air temperatures across Alaska and the Arctic have increased more than twice as fast as the global average temperature.[117,118,119,120,121,122] As surface temperatures increase, permafrost—previously permanently frozen ground—is thawing and becoming more discontinuous.[123] This triggers another self-reinforcing cycle, the permafrost–carbon feedback, where carbon previously stored in solid form is released from the ground as carbon dioxide and methane (a greenhouse gas 35 times more powerful than CO_2, on a mass basis, over a 100-year time horizon), resulting in additional warming.[25,122] The overall magnitude of the permafrost–carbon feedback is uncertain, but it is very likely that it is already amplifying carbon emissions and human-induced warming and will continue to do so.[124,125,126] Permafrost emissions imply an even greater decrease in emissions from human activities would be required to hold global temperature below a given amount of warming, such as the levels discussed in Box 2.4.

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

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

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

Diminishing Arctic Sea Ice

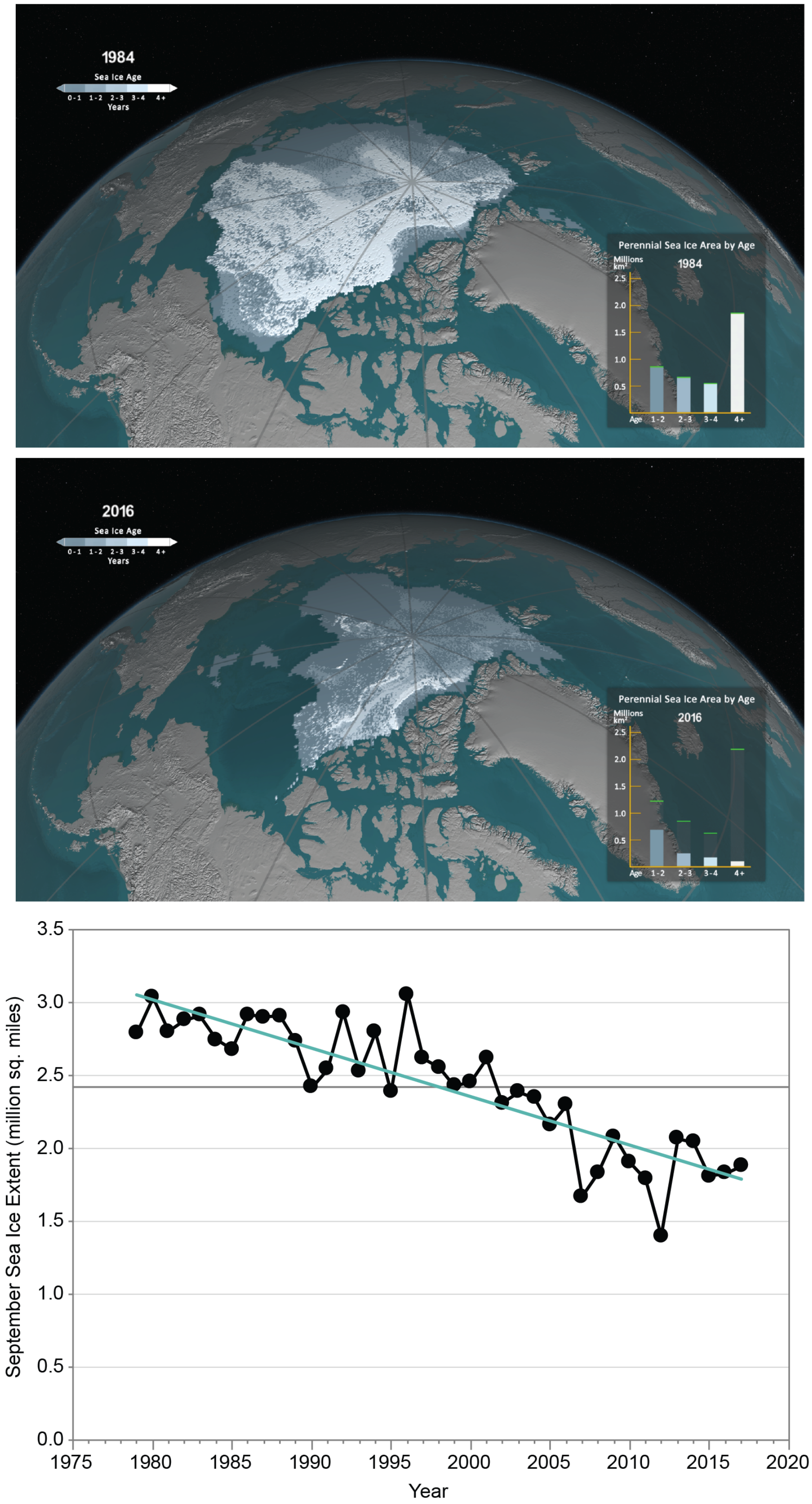


Figure 2.7: As the Arctic warms, sea ice is shrinking and becoming thinner and younger. The top and middle panels show how the summer minimum ice extent and average age, measured in September of each year, changed from 1984 (top) to 2016 (middle). An animation of the complete time series is available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

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

Key Message 8

Changes in Severe Storms

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

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

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

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

Box 2.5: The 2017 Atlantic Hurricane Season

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

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

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

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

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

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

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

2017 Tropical Cyclone Tracks

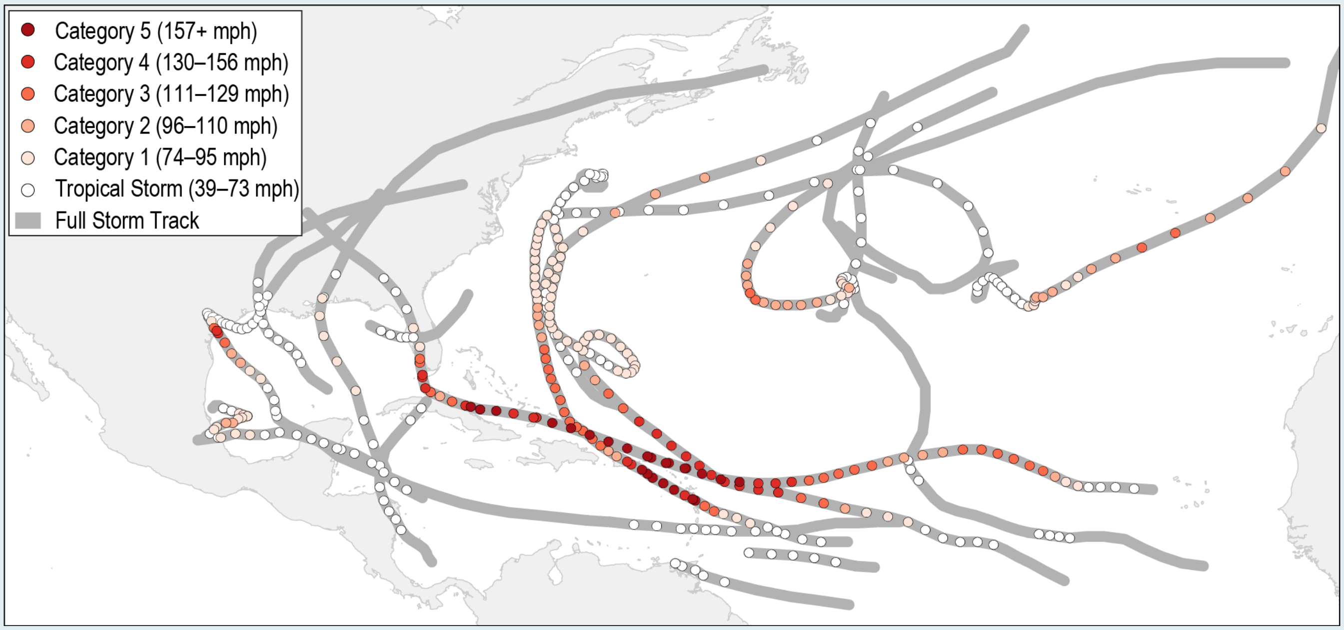


Figure 2.8: Tropical cyclone tracks for the 2017 Atlantic hurricane season. Data are based on the preliminary "operational best-track" provided by the NOAA National Hurricane Center and may change slightly after post-season reanalysis is completed. Sources: NOAA NCEI and ERT, Inc.

Notable 2017 Hurricanes

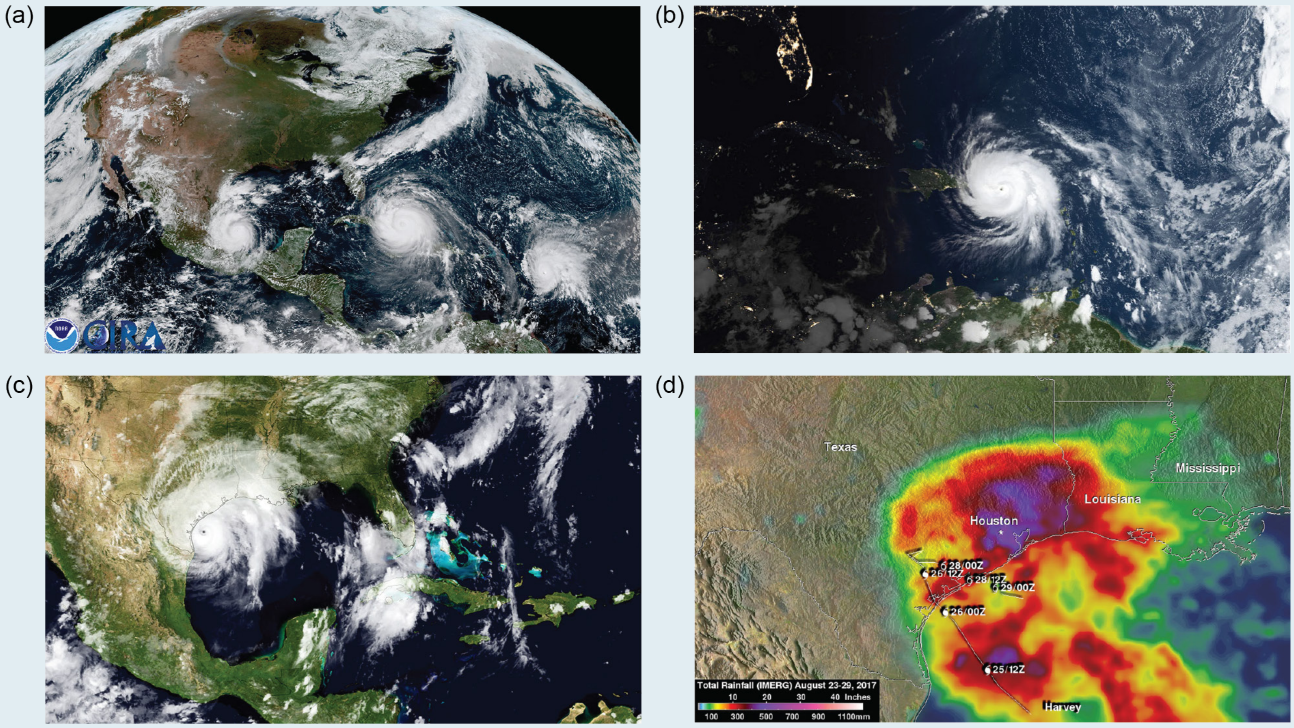


Figure 2.9: (a) Visible imagery from the GOES satellite shows Hurricanes Katia (west), Irma (center) and Jose (east) stretched across the Atlantic on September 8, 2017; (b) Hurricane Maria about to make landfall over Puerto Rico on September 19, 2017; (c) Hurricane Harvey making landfall in Texas on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

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

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

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

Box 2.6: Severe Weather

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

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

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

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

Key Message 9

Increases in Coastal Flooding

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

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

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

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

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

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

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

Key Message 10

Long-Term Changes

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

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

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

Box 2.7: Climate Models and Downscaling

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

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

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

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

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

Box 2.7: Climate Models and Downscaling, *continued*

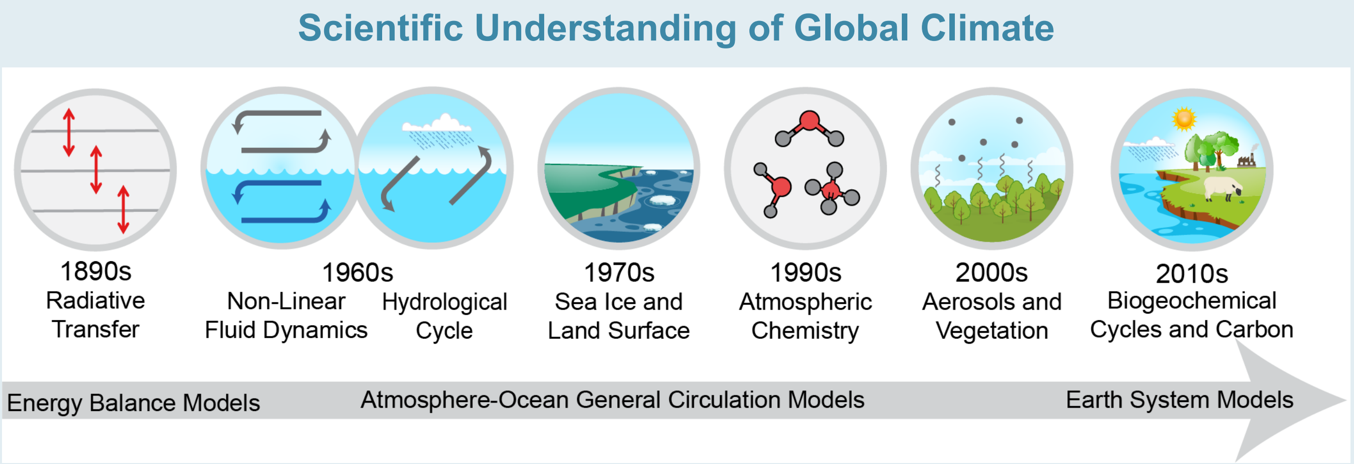


Figure 2.10: As scientific understanding of climate has evolved over the last 120 years, increasing amounts of physics, chemistry, and biology have been incorporated into calculations and, eventually, models. This figure shows when various processes and components of the climate system became regularly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

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

Acknowledgments

Technical Contributors

Robert E. Kopp
Rutgers University

Kenneth E. Kunkel
North Carolina State University

John Nielsen-Gammon
Texas A&M University

USGCRP Coordinators

David J. Dokken
Senior Program Officer

David Reidmiller
Director

Opening Image Credit

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

Traceable Accounts

Process Description

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

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

Key Message 1

Observed Changes in Global Climate

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

Description of evidence base

The Key Message and supporting text summarize extensive evidence documented in the climate science literature and are similar to statements made in previous national (NCA3)[1] and international[249] assessments. The human effects on climate have been well documented through many papers in the peer reviewed scientific literature (e.g., see Fahey et al. 2017[18] and Knutson et al. 2017[16] for more discussion of supporting evidence).

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

Major uncertainties

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

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

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

Description of confidence and likelihood

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

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

Key Message 2

Future Changes in Global Climate

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

Description of evidence base

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

Major uncertainties

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

Description of confidence and likelihood

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

Key Message 3

Warming and Acidifying Oceans

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

Description of evidence base

The Key Message and supporting text summarize the evidence documented in climate science literature as summarized in Rhein et al. (2013).[31] Oceanic warming has been documented in a variety of data sources, most notably by the World Ocean Circulation Experiment (WOCE),[251] Argo,[252] and the Extended Reconstructed Sea Surface Temperature v4 (ERSSTv4).[253] There is particular confidence in calculated warming for the time period since 1971 due to increased spatial and depth coverage and the level of agreement among independent sea surface temperature (SST) observations from satellites, surface drifters and ships, and independent studies using differing analyses, bias corrections, and data sources.[20,33,68] Other observations such as the increase in mean sea level rise (see Sweet et al. 2017[76]) and reduced Arctic/Antarctic ice sheets (see Taylor et al. 2017[122]) further confirm the increase in thermal expansion. For the purpose of extending the selected time periods back from 1900 to 2016 and analyzing U.S. regional SSTs, the ERSSTv4[253] is used. For the centennial time scale changes over 1900–2016, warming trends in all regions are statistically significant with the 95% confidence level. U.S. regional SST warming is similar between calculations using ERSSTv4 in this report and those published by Belkin (2016),[254] suggesting confidence in these findings.

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

Major uncertainties

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

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

Description of confidence and likelihood

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

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

Key Message 4

Rising Global Sea Levels

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

Description of evidence base

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

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

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

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

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

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

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

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

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

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

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

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

Major uncertainties

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

Since NCA3, multiple different approaches have been used to generate probabilistic projections of GMSL rise, conditional upon the RCPs. These approaches are in general agreement. However, emerging results indicate that marine-based sectors of the Antarctic ice sheet are more unstable than previous modeling indicated. The rate of ice sheet mass changes remains challenging to project.

Description of confidence and likelihood

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

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

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

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

Key Message 5

Increasing U.S. Temperatures

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

Description of evidence base

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

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

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

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

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

Major uncertainties

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

Global climate models are subject to structural and parametric uncertainty, resulting in a range of estimates of future changes in average temperature. This is partially mitigated through the use of model weighting and pattern scaling. Furthermore, virtually every ensemble member of every model projection contains an increase in temperature by mid- and late-century. Empirical downscaling introduces additional uncertainty (e.g., with respect to stationarity).

Description of confidence and likelihood

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

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

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

Key Message 6

Changing U.S. Precipitation

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

Description of evidence base

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

Numerous papers have been written documenting observed changes in heavy precipitation events in the United States (e.g., Kunkel et al. 2003, Groisman et al. 2004[275,276]), which were cited in the Third National Climate Assessment, as well as those cited in this assessment. Although station-based analyses (e.g., Westra et al. 2013[277]) do not show large numbers of statistically significant station-based trends, area averaging reduces the noise inherent in station-based data and produces robust increasing signals (see Easterling et al. 2017,[94] Figures 7.2 and 7.3). Evidence of long-term changes in precipitation is based on analysis of daily precipitation observations from the U.S. Cooperative Observer Network (http://www.nws.noaa.gov/om/coop/) and shown in Easterling et al. (2017),[94] Figures 7.2, 7.3, and 7.4.

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

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

Major uncertainties

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

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

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

Description of confidence and likelihood

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

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

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

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

Key Message 7

Rapid Arctic Change

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

Description of evidence base

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

This aspect of the Key Message is supported by observational evidence from ground-based observing stations, satellites, and data model temperature analyses from multiple sources and independent analysis techniques.[117,118,119,120,121,136,278] For more than 40 years, climate models have predicted enhanced arctic warming, indicating a solid grasp of the underlying physics and positive feedbacks driving the accelerated arctic warming.[26,279,280] Lastly, similar statements have been made in NCA3,[1] IPCC AR5,[120] and in other arctic-specific assessments such as the Arctic Climate Impacts Assessment[281] and the Snow, Water, Ice and Permafrost in the Arctic assessment report.[129]

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

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

Arctic land and sea ice loss observed in the last three decades continues, in some cases accelerating. A diverse range of observational evidence from multiple data sources and independent analysis techniques provides consistent evidence of substantial declines in arctic sea ice extent, thickness, and volume since at least 1979, mountain glacier melt over the last 50 years, and accelerating mass loss from Greenland. An array of different models and independent analyses indicate that future declines in ice across the Arctic are expected, resulting in late summers in the Arctic very likely becoming ice free by mid-century.

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

Major uncertainties

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

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

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

Description of confidence and likelihood

Thre is *very high confidence* that the arctic surface and air temperatures have warmed across Alaska and the Arctic at a much faster rate than the global average is provided by the multiple datasets analyzed by multiple independent groups indicating the same conclusion. Additionally, climate models capture the enhanced warming in the Arctic, indicating a solid understanding of the underlying physical mechanisms.

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

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

Key Message 8

Changes in Severe Storms

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

Description of evidence base

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

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

Models are generally in agreement that tropical cyclones will be more intense and have higher precipitation rates, at least in most basins. Given the agreement among models and support of theory and mechanistic understanding, there is *medium to high confidence* in the overall projection, although there is some limitation on confidence levels due to the lack of a supporting detectable anthropogenic contribution to tropical cyclone intensities or precipitation rates.

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

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

Major uncertainties

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

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

In terms of atmospheric rivers (ARs), a modest uncertainty remains in the lack of a supporting detectable anthropogenic signal in the historical data to add further confidence to these projections. However, the overall increase in ARs projected/expected is based to a very large degree on *very high confidence* that the atmospheric water vapor will increase. Thus, increasing water vapor coupled with little projected change in wind structure/intensity still indicates increases in the frequency/intensity of ARs. A modest uncertainty arises in quantifying the expected change at a regional level (for example, northern Oregon, versus southern Oregon), given that there are some changes expected in the position of the jet stream that might influence the degree of increase for different locations along the west coast. Uncertainty in the projections of the number and intensity of ARs is introduced by uncertainties in the models' ability to represent ARs and their interactions with climate.

Description of confidence and likelihood

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

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

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

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

Key Message 9

Increases in Coastal Flooding

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

Description of evidence base

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

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

Major uncertainties

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

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

Description of confidence and likelihood

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

Key Message 10

Long-Term Changes

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

Description of evidence base

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

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

Major uncertainties

The largest uncertainties are 1) whether proposed tipping elements actually undergo critical transitions, 2) the magnitude and timing of forcing that will be required to initiate critical transitions in tipping elements, 3) the speed of the transition once it has been triggered, 4) the characteristics of the new state that results from such transition, and 5) the potential for new positive feedbacks and tipping elements to exist that are yet unknown.

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

Description of confidence and likelihood

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

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

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

References

1. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds., 2014: *Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program, Washington, DC, 841 pp. http://dx.doi.org/10.7930/J0Z31WJ2

2. NASA, 2017: NASA, NOAA Data Show 2016 Warmest Year on Record Globally. NASA, Washington, DC, January 18. https://www.nasa.gov/press-release/nasa-noaa-data-show-2016-warmest-year-on-record-globally/

3. NCEI, 2016: Climate at a Glance. Global Time Series: Global Land and Ocean Temperature Anomalies, 1880–2015 [web tool]. NOAA National Centers for Environmental Information (NCEI), Asheville, NC. http://www.ncdc.noaa.gov/cag/time-series/global/globe/land_ocean/ytd/12/1880-2015

4. Lewandowsky, S., J.S. Risbey, and N. Oreskes, 2016: The "pause" in global warming: Turning a routine fluctuation into a problem for science. *Bulletin of the American Meteorological Society*, **97** (5), 723-733. http://dx.doi.org/10.1175/BAMS-D-14-00106.1

5. Santer, B.D., S. Soloman, F.J. Wentz, Q. Fu, S. Po-Chedley, C. Mears, J.F. Painter, and C. Bonfils, 2017: Tropospheric warming over the past two decades. *Scientific Reports*, **7**, 2336. http://dx.doi.org/10.1038/s41598-017-02520-7

6. Karl, T.R., A. Arguez, B. Huang, J.H. Lawrimore, J.R. McMahon, M.J. Menne, T.C. Peterson, R.S. Vose, and H.-M. Zhang, 2015: Possible artifacts of data biases in the recent global surface warming hiatus. *Science*, **348** (6242), 1469-1472. http://dx.doi.org/10.1126/science.aaa5632

7. Mears, C.A. and F.J. Wentz, 2016: Sensitivity of satellite-derived tropospheric temperature trends to the diurnal cycle adjustment. *Journal of Climate*, **29** (10), 3629-3646. http://dx.doi.org/10.1175/JCLI-D-15-0744.1

8. Richardson, M., K. Cowtan, E. Hawkins, and M.B. Stolpe, 2016: Reconciled climate response estimates from climate models and the energy budget of Earth. *Nature Climate Change*, **6**, 931-935. http://dx.doi.org/10.1038/nclimate3066

9. Hausfather, Z., K. Cowtan, D.C. Clarke, P. Jacobs, M. Richardson, and R. Rohde, 2017: Assessing recent warming using instrumentally homogeneous sea surface temperature records. *Science Advances*, **3** (1), e1601207. http://dx.doi.org/10.1126/sciadv.1601207

10. 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. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 35-72. http://dx.doi.org/10.7930/J08S4N35

11. PAGES 2K Consortium, 2013: Continental-scale temperature variability during the past two millennia. *Nature Geoscience*, **6** (5), 339-346. http://dx.doi.org/10.1038/ngeo1797

12. Blunden, J. and D.S. Arndt, 2016: State of the climate in 2015. *Bulletin of the American Meteorological Society*, **97** (8), Si-S275. http://dx.doi.org/10.1175/2016BAMSStateoftheClimate.1

13. Meehl, G.A., C. Tebaldi, and D. Adams-Smith, 2016: US daily temperature records past, present, and future. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (49), 13977-13982. http://dx.doi.org/10.1073/pnas.1606117113

14. EPA, 2016: Climate Change Indicators in the United States, 2016. 4th edition. EPA 430-R-16-004. U.S. Environmental Protection Agency, Washington, DC, 96 pp. https://www.epa.gov/sites/production/files/2016-08/documents/climate_indicators_2016.pdf

15. Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013: Detection and attribution of climate change: From global to regional. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–952. http://www.climatechange2013.org/report/full-report/

16. Knutson, T., J.P. Kossin, C. Mears, J. Perlwitz, and M.F. Wehner, 2017: Detection and attribution of climate change. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 114-132. http://dx.doi.org/10.7930/J01834ND

17. Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, 2013: Anthropogenic and natural radiative forcing. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659–740. http://www.climatechange2013.org/report/full-report/

18. Fahey, D.W., S. Doherty, K.A. Hibbard, A. Romanou, and P.C. Taylor, 2017: Physical drivers of climate change. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 73-113. http://dx.doi.org/10.7930/J0513WCR

19. Marcott, S.A., J.D. Shakun, P.U. Clark, and A.C. Mix, 2013: A reconstruction of regional and global temperature for the past 11,300 years. *Science*, **339** (6124), 1198-1201. http://dx.doi.org/10.1126/science.1228026

20. Cheng, L., K.E. Trenberth, J. Fasullo, T. Boyer, J. Abraham, and J. Zhu, 2017: Improved estimates of ocean heat content from 1960 to 2015. *Science Advances*, **3** (3), e1601545. http://dx.doi.org/10.1126/sciadv.1601545

21. Church, J.A., N.J. White, L.F. Konikow, C.M. Domingues, J.G. Cogley, E. Rignot, J.M. Gregory, M.R. van den Broeke, A.J. Monaghan, and I. Velicogna, 2011: Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters*, **38** (18), L18601. http://dx.doi.org/10.1029/2011GL048794

22. Anderson, B.T., J.R. Knight, M.A. Ringer, J.-H. Yoon, and A. Cherchi, 2012: Testing for the possible influence of unknown climate forcings upon global temperature increases from 1950 to 2000. *Journal of Climate*, **25** (20), 7163-7172. http://dx.doi.org/10.1175/jcli-d-11-00645.1

23. Hawkins, E. and R. Sutton, 2009: The potential to narrow uncertainty in regional climate predictions. *Bulletin of the American Meteorological Society*, **90** (8), 1095-1107. http://dx.doi.org/10.1175/2009BAMS2607.1

24. Hayhoe, K., J. Edmonds, R.E. Kopp, A.N. LeGrande, B.M. Sanderson, M.F. Wehner, and D.J. Wuebbles, 2017: Climate models, scenarios, and projections. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 133-160. http://dx.doi.org/10.7930/J0WH2N54

25. Kopp, R.E., D.R. Easterling, T. Hall, K. Hayhoe, R. Horton, K.E. Kunkel, and A.N. LeGrande, 2017: Potential surprises—Compound extremes and tipping elements. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 411-429. http://dx.doi.org/10.7930/J0GB227J

26. Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner, 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1029–1136. http://www.climatechange2013.org/report/full-report/

27. DeAngelo, B., J. Edmonds, D.W. Fahey, and B.M. Sanderson, 2017: Perspectives on climate change mitigation. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 393-410. http://dx.doi.org/10.7930/J0M32SZG

28. Friedlingstein, P., S. Solomon, G.K. Plattner, R. Knutti, P. Ciais, and M.R. Raupach, 2011: Long-term climate implications of twenty-first century options for carbon dioxide emission mitigation. *Nature Climate Change*, **1**, 457-461. http://dx.doi.org/10.1038/nclimate1302

29. Solomon, S., G.K. Plattner, R. Knutti, and P. Friedlingstein, 2009: Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences of the United States of America*, **106** (6), 1704-1709. http://dx.doi.org/10.1073/pnas.0812721106

30. Clark, P.U., J.D. Shakun, S.A. Marcott, A.C. Mix, M. Eby, S. Kulp, A. Levermann, G.A. Milne, P.L. Pfister, B.D. Santer, D.P. Schrag, S. Solomon, T.F. Stocker, B.H. Strauss, A.J. Weaver, R. Winkelmann, D. Archer, E. Bard, A. Goldner, K. Lambeck, R.T. Pierrehumbert, and G.-K. Plattner, 2016: Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change*, **6** (4), 360-369. http://dx.doi.org/10.1038/nclimate2923

31. Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley, and F. Wang, 2013: Observations: Ocean. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 255–316. http://www.climatechange2013.org/report/full-report/

32. Gattuso, J.-P., A. Magnan, R. Billé, W.W.L. Cheung, E.L. Howes, F. Joos, D. Allemand, L. Bopp, S.R. Cooley, C.M. Eakin, O. Hoegh-Guldberg, R.P. Kelly, H.-O. Pörtner, A.D. Rogers, J.M. Baxter, D. Laffoley, D. Osborn, A. Rankovic, J. Rochette, U.R. Sumaila, S. Treyer, and C. Turley, 2015: Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science*, **349** (6243), aac4722. http://dx.doi.org/10.1126/science.aac4722

33. Levitus, S., J.I. Antonov, T.P. Boyer, O.K. Baranova, H.E. Garcia, R.A. Locarnini, A.V. Mishonov, J.R. Reagan, D. Seidov, E.S. Yarosh, and M.M. Zweng, 2012: World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010. *Geophysical Research Letters*, **39** (10), L10603. http://dx.doi.org/10.1029/2012GL051106

34. Jewett, L. and A. Romanou, 2017: Ocean acidification and other ocean changes. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 364-392. http://dx.doi.org/10.7930/J0QV3JQB

35. Le Quéré, C., R.M. Andrew, J.G. Canadell, S. Sitch, J.I. Korsbakken, G.P. Peters, A.C. Manning, T.A. Boden, P.P. Tans, R.A. Houghton, R.F. Keeling, S. Alin, O.D. Andrews, P. Anthoni, L. Barbero, L. Bopp, F. Chevallier, L.P. Chini, P. Ciais, K. Currie, C. Delire, S.C. Doney, P. Friedlingstein, T. Gkritzalis, I. Harris, J. Hauck, V. Haverd, M. Hoppema, K. Klein Goldewijk, A.K. Jain, E. Kato, A. Körtzinger, P. Landschützer, N. Lefèvre, A. Lenton, S. Lienert, D. Lombardozzi, J.R. Melton, N. Metzl, F. Millero, P.M.S. Monteiro, D.R. Munro, J.E.M.S. Nabel, S.I. Nakaoka, K. O'Brien, A. Olsen, A.M. Omar, T. Ono, D. Pierrot, B. Poulter, C. Rödenbeck, J. Salisbury, U. Schuster, J. Schwinger, R. Séférian, I. Skjelvan, B.D. Stocker, A.J. Sutton, T. Takahashi, H. Tian, B. Tilbrook, I.T. van der Laan-Luijkx, G.R. van der Werf, N. Viovy, A.P. Walker, A.J. Wiltshire, and S. Zaehle, 2016: Global carbon budget 2016. *Earth System Science Data*, **8** (2), 605-649. http://dx.doi.org/10.5194/essd-8-605-2016

36. Feely, R.A., C.L. Sabine, K. Lee, W. Berelson, J. Kleypas, V.J. Fabry, and F.J. Millero, 2004: Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science*, **305** (5682), 362-366. http://dx.doi.org/10.1126/science.1097329

37. Borges, A.V. and N. Gypens, 2010: Carbonate chemistry in the coastal zone responds more strongly to eutrophication than ocean acidification. *Limnology and Oceanography*, **55** (1), 346-353. http://dx.doi.org/10.4319/lo.2010.55.1.0346

38. Waldbusser, G.G. and J.E. Salisbury, 2014: Ocean acidification in the coastal zone from an organism's perspective: Multiple system parameters, frequency domains, and habitats. *Annual Review of Marine Science*, **6** (1), 221-247. http://dx.doi.org/10.1146/annurev-marine-121211-172238

39. Hendriks, I.E., C.M. Duarte, Y.S. Olsen, A. Steckbauer, L. Ramajo, T.S. Moore, J.A. Trotter, and M. McCulloch, 2015: Biological mechanisms supporting adaptation to ocean acidification in coastal ecosystems. *Estuarine, Coastal and Shelf Science*, **152**, A1-A8. http://dx.doi.org/10.1016/j.ecss.2014.07.019

40. Sutton, A.J., C.L. Sabine, R.A. Feely, W.J. Cai, M.F. Cronin, M.J. McPhaden, J.M. Morell, J.A. Newton, J.H. Noh, S.R. Ólafsdóttir, J.E. Salisbury, U. Send, D.C. Vandemark, and R.A. Weller, 2016: Using present-day observations to detect when anthropogenic change forces surface ocean carbonate chemistry outside preindustrial bounds. *Biogeosciences*, **13** (17), 5065-5083. http://dx.doi.org/10.5194/bg-13-5065-2016

41. Feely, R.A., S.C. Doney, and S.R. Cooley, 2009: Ocean acidification: Present conditions and future changes in a high-CO_2 world. *Oceanography*, **22** (4), 36-47. http://dx.doi.org/10.5670/oceanog.2009.95

42. Harris, K.E., M.D. DeGrandpre, and B. Hales, 2013: Aragonite saturation state dynamics in a coastal upwelling zone. *Geophysical Research Letters*, **40** (11), 2720-2725. http://dx.doi.org/10.1002/grl.50460

43. Helm, K.P., N.L. Bindoff, and J.A. Church, 2011: Observed decreases in oxygen content of the global ocean. *Geophysical Research Letters*, **38** (23), L23602. http://dx.doi.org/10.1029/2011GL049513

44. Roemmich, D., J. Church, J. Gilson, D. Monselesan, P. Sutton, and S. Wijffels, 2015: Unabated planetary warming and its ocean structure since 2006. *Nature Climate Change*, **5** (3), 240-245. http://dx.doi.org/10.1038/nclimate2513

45. Stramma, L., S. Schmidtko, L.A. Levin, and G.C. Johnson, 2010: Ocean oxygen minima expansions and their biological impacts. *Deep Sea Research Part I: Oceanographic Research Papers*, **57** (4), 587-595. http://dx.doi.org/10.1016/j.dsr.2010.01.005

46. Justić, D., T. Legović, and L. Rottini-Sandrini, 1987: Trends in oxygen content 1911–1984 and occurrence of benthic mortality in the northern Adriatic Sea. *Estuarine, Coastal and Shelf Science*, **25** (4), 435-445. http://dx.doi.org/10.1016/0272-7714(87)90035-7

47. Zaitsev, Y.P., 1992: Recent changes in the trophic structure of the Black Sea. *Fisheries Oceanography*, **1** (2), 180-189. http://dx.doi.org/10.1111/j.1365-2419.1992.tb00036.x

48. Conley, D.J., J. Carstensen, J. Aigars, P. Axe, E. Bonsdorff, T. Eremina, B.-M. Haahti, C. Humborg, P. Jonsson, J. Kotta, C. Lännegren, U. Larsson, A. Maximov, M.R. Medina, E. Lysiak-Pastuszak, N. Remeikaitė-Nikienė, J. Walve, S. Wilhelms, and L. Zillén, 2011: Hypoxia is increasing in the coastal zone of the Baltic Sea. *Environmental Science & Technology*, **45** (16), 6777-6783. http://dx.doi.org/10.1021/es201212r

49. Brush, G.S., 2009: Historical land use, nitrogen, and coastal eutrophication: A paleoecological perspective. *Estuaries and Coasts*, **32** (1), 18-28. http://dx.doi.org/10.1007/s12237-008-9106-z

50. Gilbert, D., B. Sundby, C. Gobeil, A. Mucci, and G.-H. Tremblay, 2005: A seventy-two-year record of diminishing deep-water oxygen in the St. Lawrence estuary: The northwest Atlantic connection. *Limnology and Oceanography*, **50** (5), 1654-1666. http://dx.doi.org/10.4319/lo.2005.50.5.1654

51. Rabalais, N.N., R.E. Turner, B.K. Sen Gupta, D.F. Boesch, P. Chapman, and M.C. Murrell, 2007: Hypoxia in the northern Gulf of Mexico: Does the science support the plan to reduce, mitigate, and control hypoxia? *Estuaries and Coasts*, **30** (5), 753-772. http://dx.doi.org/10.1007/bf02841332

52. Booth, J.A.T., E.E. McPhee-Shaw, P. Chua, E. Kingsley, M. Denny, R. Phillips, S.J. Bograd, L.D. Zeidberg, and W.F. Gilly, 2012: Natural intrusions of hypoxic, low pH water into nearshore marine environments on the California coast. *Continental Shelf Research*, **45**, 108-115. http://dx.doi.org/10.1016/j.csr.2012.06.009

53. Bopp, L., L. Resplandy, J.C. Orr, S.C. Doney, J.P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T. Ilyina, R. Séférian, J. Tjiputra, and M. Vichi, 2013: Multiple stressors of ocean ecosystems in the 21st century: Projections with CMIP5 models. *Biogeosciences*, **10** (10), 6225-6245. http://dx.doi.org/10.5194/bg-10-6225-2013

54. Hönisch, B., A. Ridgwell, D.N. Schmidt, E. Thomas, S.J. Gibbs, A. Sluijs, R. Zeebe, L. Kump, R.C. Martindale, S.E. Greene, W. Kiessling, J. Ries, J.C. Zachos, D.L. Royer, S. Barker, T.M. Marchitto, Jr., R. Moyer, C. Pelejero, P. Ziveri, G.L. Foster, and B. Williams, 2012: The geological record of ocean acidification. *Science*, **335** (6072), 1058-1063. http://dx.doi.org/10.1126/science.1208277

55. Zeebe, R.E., A. Ridgwell, and J.C. Zachos, 2016: Anthropogenic carbon release rate unprecedented during the past 66 million years. *Nature Geoscience*, **9** (4), 325-329. http://dx.doi.org/10.1038/ngeo2681

56. Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer, and A.S. Unnikrishnan, 2013: Sea level change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1137–1216. http://www.climatechange2013.org/report/full-report/

57. Sweet, W.V., R. Horton, R.E. Kopp, A.N. LeGrande, and A. Romanou, 2017: Sea level rise. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 333-363. http://dx.doi.org/10.7930/J0VM49F2

58. Kopp, R.E., A.C. Kemp, K. Bittermann, B.P. Horton, J.P. Donnelly, W.R. Gehrels, C.C. Hay, J.X. Mitrovica, E.D. Morrow, and S. Rahmstorf, 2016: Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (11), E1434-E1441. http://dx.doi.org/10.1073/pnas.1517056113

59. Slangen, A.B.A., J.A. Church, X. Zhang, and D. Monselesan, 2014: Detection and attribution of global mean thermosteric sea level change. *Geophysical Research Letters*, **41** (16), 5951-5959. http://dx.doi.org/10.1002/2014GL061356

60. Slangen, A.B.A., J.A. Church, C. Agosta, X. Fettweis, B. Marzeion, and K. Richter, 2016: Anthropogenic forcing dominates global mean sea-level rise since 1970. *Nature Climate Change*, **6**, 701-705. http://dx.doi.org/10.1038/nclimate2991

61. Jevrejeva, S., A. Grinsted, and J.C. Moore, 2009: Anthropogenic forcing dominates sea level rise since 1850. *Geophysical Research Letters*, **36** (20), L20706. http://dx.doi.org/10.1029/2009GL040216

62. Marzeion, B., J.G. Cogley, K. Richter, and D. Parkes, 2014: Attribution of global glacier mass loss to anthropogenic and natural causes. *Science*, **345** (6199), 919-921. http://dx.doi.org/10.1126/science.1254702

63. Marcos, M., B. Marzeion, S. Dangendorf, A.B.A. Slangen, H. Palanisamy, and L. Fenoglio-Marc, 2017: Internal variability versus anthropogenic forcing on sea level and its components. *Surveys in Geophysics*, **38**, 329–348. http://dx.doi.org/10.1007/s10712-016-9373-3

64. Reager, J.T., A.S. Gardner, J.S. Famiglietti, D.N. Wiese, A. Eicker, and M.-H. Lo, 2016: A decade of sea level rise slowed by climate-driven hydrology. *Science*, **351** (6274), 699-703. http://dx.doi.org/10.1126/science.aad8386

65. Rietbroek, R., S.-E. Brunnabend, J. Kusche, J. Schröter, and C. Dahle, 2016: Revisiting the contemporary sea-level budget on global and regional scales. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (6), 1504-1509. http://dx.doi.org/10.1073/pnas.1519132113

66. Wada, Y., M.-H. Lo, P.J.F. Yeh, J.T. Reager, J.S. Famiglietti, R.-J. Wu, and Y.-H. Tseng, 2016: Fate of water pumped from underground and contributions to sea-level rise. *Nature Climate Change*, **6** (8), 777-780. http://dx.doi.org/10.1038/nclimate3001

67. Wada, Y., J.T. Reager, B.F. Chao, J. Wang, M.-H. Lo, C. Song, Y. Li, and A.S. Gardner, 2017: Recent changes in land water storage and its contribution to sea level variations. *Surveys in Geophysics*, **38** (1), 131-152. http://dx.doi.org/10.1007/s10712-016-9399-6

68. Llovel, W., J.K. Willis, F.W. Landerer, and I. Fukumori, 2014: Deep-ocean contribution to sea level and energy budget not detectable over the past decade. *Nature Climate Change*, **4** (11), 1031-1035. http://dx.doi.org/10.1038/nclimate2387

69. Leuliette, E.W., 2015: The balancing of the sea-level budget. *Current Climate Change Reports*, **1** (3), 185-191. http://dx.doi.org/10.1007/s40641-015-0012-8

70. Merrifield, M.A., P. Thompson, E. Leuliette, G.T. Mitchum, D.P. Chambers, S. Jevrejeva, R.S. Nerem, M. Menéndez, W. Sweet, B. Hamlington, and J.J. Marra, 2015: [Global Oceans] Sea level variability and change [in “State of the Climate in 2014”]. *Bulletin of the American Meteorological Society*, **96 (12)** (7), S82-S85. http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

71. Chambers, D.P., A. Cazenave, N. Champollion, H. Dieng, W. Llovel, R. Forsberg, K. von Schuckmann, and Y. Wada, 2017: Evaluation of the global mean sea level budget between 1993 and 2014. *Surveys in Geophysics*, **38**, 309–327. http://dx.doi.org/10.1007/s10712-016-9381-3

72. Leuliette, E.W. and R.S. Nerem, 2016: Contributions of Greenland and Antarctica to global and regional sea level change. *Oceanography*, **29** (4), 154-159. http://dx.doi.org/10.5670/oceanog.2016.107

73. Hay, C.C., E. Morrow, R.E. Kopp, and J.X. Mitrovica, 2015: Probabilistic reanalysis of twentieth-century sea-level rise. *Nature*, **517** (7535), 481-484. http://dx.doi.org/10.1038/nature14093

74. Church, J.A. and N.J. White, 2011: Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics*, **32** (4-5), 585-602. http://dx.doi.org/10.1007/s10712-011-9119-1

75. Nerem, R.S., D.P. Chambers, C. Choe, and G.T. Mitchum, 2010: Estimating mean sea level change from the TOPEX and Jason altimeter missions. *Marine Geodesy*, **33** (S1), 435-446. http://dx.doi.org/10.1080/01490419.2010.491031

76. Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler, and C. Zervas, 2017: Global and Regional Sea Level Rise Scenarios for the United States. NOAA Tech. Rep. NOS CO-OPS 083. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 75 pp. https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf

77. Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss, and C. Tebaldi, 2014: Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, **2** (8), 383-406. http://dx.doi.org/10.1002/2014EF000239

78. Jevrejeva, S., A. Grinsted, and J.C. Moore, 2014: Upper limit for sea level projections by 2100. *Environmental Research Letters*, **9** (10), 104008. http://dx.doi.org/10.1088/1748-9326/9/10/104008

79. Grinsted, A., S. Jevrejeva, R.E.M. Riva, and D. Dahl-Jensen, 2015: Sea level rise projections for northern Europe under RCP8.5. *Climate Research*, **64** (1), 15-23. http://dx.doi.org/10.3354/cr01309

80. DeConto, R.M. and D. Pollard, 2016: Contribution of Antarctica to past and future sea-level rise. *Nature*, **531** (7596), 591-597. http://dx.doi.org/10.1038/nature17145

81. Kopp, R.E., R.M. DeConto, D.A. Bader, C.C. Hay, R.M. Horton, S. Kulp, M. Oppenheimer, D. Pollard, and B.H. Strauss, 2017: Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections. *Earth's Future*, **5** (12), 1217-1233. http://dx.doi.org/10.1002/2017EF000663

82. Strauss, B.H., S. Kulp, and A. Levermann, 2015: Carbon choices determine US cities committed to futures below sea level. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (44), 13508-13513. http://dx.doi.org/10.1073/pnas.1511186112

83. Kopp, R.E., F.J. Simons, J.X. Mitrovica, A.C. Maloof, and M. Oppenheimer, 2009: Probabilistic assessment of sea level during the last interglacial stage. *Nature*, **462** (7275), 863-867. http://dx.doi.org/10.1038/nature08686

84. Dutton, A., A.E. Carlson, A.J. Long, G.A. Milne, P.U. Clark, R. DeConto, B.P. Horton, S. Rahmstorf, and M.E. Raymo, 2015: Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science*, **349** (6244), aaa4019. http://dx.doi.org/10.1126/science.aaa4019

85. Vose, R.S., D.R. Easterling, K.E. Kunkel, A.N. LeGrande, and M.F. Wehner, 2017: Temperature changes in the United States. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 185-206. http://dx.doi.org/10.7930/J0N29V45

86. Trouet, V., H.F. Diaz, E.R. Wahl, A.E. Viau, R. Graham, N. Graham, and E.R. Cook, 2013: A 1500-year reconstruction of annual mean temperature for temperate North America on decadal-to-multidecadal time scales. *Environmental Research Letters*, **8** (2), 024008. http://dx.doi.org/10.1088/1748-9326/8/2/024008

87. Meehl, G.A., J.M. Arblaster, and G. Branstator, 2012: Mechanisms contributing to the warming hole and the consequent US east–west differential of heat extremes. *Journal of Climate*, **25** (2012), 6394-6408. http://dx.doi.org/10.1175/JCLI-D-11-00655.1

88. Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our changing climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 19-67. http://dx.doi.org/10.7930/J0KW5CXT

89. Pan, Z., X. Liu, S. Kumar, Z. Gao, and J. Kinter, 2013: Intermodel variability and mechanism attribution of central and southeastern U.S. anomalous cooling in the twentieth century as simulated by CMIP5 models. *Journal of Climate*, **26** (17), 6215-6237. http://dx.doi.org/10.1175/JCLI-D-12-00559.1

90. Hibbard, K.A., F.M. Hoffman, D. Huntzinger, and T.O. West, 2017: Changes in land cover and terrestrial biogeochemistry. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 277-302. http://dx.doi.org/10.7930/J0416V6X

91. Cook, B.I., R.L. Miller, and R. Seager, 2009: Amplification of the North American "Dust Bowl" drought through human-induced land degradation. *Proceedings of the National Academy of Sciences of the United States of America*, **106** (13), 4997-5001. http://dx.doi.org/10.1073/pnas.0810200106

92. Donat, M.G., A.D. King, J.T. Overpeck, L.V. Alexander, I. Durre, and D.J. Karoly, 2016: Extraordinary heat during the 1930s US Dust Bowl and associated large-scale conditions. *Climate Dynamics*, **46** (1), 413-426. http://dx.doi.org/10.1007/s00382-015-2590-5

93. Cowan, T., G.C. Hegerl, I. Colfescu, M. Bollasina, A. Purich, and G. Boschat, 2017: Factors contributing to record-breaking heat waves over the Great Plains during the 1930s Dust Bowl. *Journal of Climate*, **30** (7), 2437-2461. http://dx.doi.org/10.1175/jcli-d-16-0436.1

94. Easterling, D.R., K.E. Kunkel, J.R. Arnold, T. Knutson, A.N. LeGrande, L.R. Leung, R.S. Vose, D.E. Waliser, and M.F. Wehner, 2017: Precipitation change in the United States. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 207-230. http://dx.doi.org/10.7930/J0H993CC

95. Quan, X.-W., M.P. Hoerling, J. Perlwitz, H.F. Diaz, and T. Xu, 2014: How fast are the tropics expanding? *Journal of Climate*, **27** (5), 1999-2013. http://dx.doi.org/10.1175/JCLI-D-13-00287.1

96. Feng, Z., L.R. Leung, S. Hagos, R.A. Houze, C.D. Burleyson, and K. Balaguru, 2016: More frequent intense and long-lived storms dominate the springtime trend in central US rainfall. *Nature Communications*, **7**, 13429. http://dx.doi.org/10.1038/ncomms13429

97. Fritsch, J.M., R.J. Kane, and C.R. Chelius, 1986: The contribution of mesoscale convective weather systems to the warm-season precipitation in the United States. *Journal of Climate and Applied Meteorology*, **25** (10), 1333-1345. http://dx.doi.org/10.1175/1520-0450(1986)025<1333:tcomcw>2.0.co;2

98. Schumacher, R.S. and R.H. Johnson, 2006: Characteristics of U.S. extreme rain events during 1999–2003. *Weather and Forecasting*, **21** (1), 69-85. http://dx.doi.org/10.1175/waf900.1

99. Hirsch, R.M. and K.R. Ryberg, 2012: Has the magnitude of floods across the USA changed with global CO_2 levels? *Hydrological Sciences Journal*, **57** (1), 1-9. http://dx.doi.org/10.1080/02626667.2011.621895

100. Hodgkins, G.A., P.H. Whitfield, D.H. Burn, J. Hannaford, B. Renard, K. Stahl, A.K. Fleig, H. Madsen, L. Mediero, J. Korhonen, C. Murphy, and D. Wilson, 2017: Climate-driven variability in the occurrence of major floods across North America and Europe. *Journal of Hydrology*, **552**, 704-717. http://dx.doi.org/10.1016/j.jhydrol.2017.07.027

101. Wehner, M.F., J.R. Arnold, T. Knutson, K.E. Kunkel, and A.N. LeGrande, 2017: Droughts, floods, and wildfires. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 231-256. http://dx.doi.org/10.7930/J0CJ8BNN

102. Brown, R.D. and D.A. Robinson, 2011: Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty. *The Cryosphere*, **5** (1), 219-229. http://dx.doi.org/10.5194/tc-5-219-2011

103. Pederson, G.T., J.L. Betancourt, and G.J. McCabe, 2013: Regional patterns and proximal causes of the recent snowpack decline in the Rocky Mountains, U.S. *Geophysical Research Letters*, **40** (9), 1811-1816. http://dx.doi.org/10.1002/grl.50424

104. Gan, T.Y., R.G. Barry, M. Gizaw, A. Gobena, and R. Balaji, 2013: Changes in North American snowpacks for 1979–2007 detected from the snow water equivalent data of SMMR and SSM/I passive microwave and related climatic factors. *Journal of Geophysical Research Atmospheres*, **118** (14), 7682-7697. http://dx.doi.org/10.1002/jgrd.50507

105. Ficklin, D.L., Y. Luo, and M. Zhang, 2013: Climate change sensitivity assessment of streamflow and agricultural pollutant transport in California's Central Valley using Latin hypercube sampling. *Hydrological Processes*, **27** (18), 2666-2675. http://dx.doi.org/10.1002/hyp.9386

106. Elsner, M.M., L. Cuo, N. Voisin, J.S. Deems, A.F. Hamlet, J.A. Vano, K.E.B. Mickelson, S.Y. Lee, and D.P. Lettenmaier, 2010: Implications of 21st century climate change for the hydrology of Washington State. *Climatic Change*, **102** (1-2), 225-260. http://dx.doi.org/10.1007/s10584-010-9855-0

107. Christensen, N.S. and D.P. Lettenmaier, 2007: A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. *Hydrology and Earth System Sciences*, **11** (4), 1417-1434. http://dx.doi.org/10.5194/hess-11-1417-2007

108. Ryu, J.-H. and K. Hayhoe, 2017: Observed and CMIP5 modeled influence of large-scale circulation on summer precipitation and drought in the South-Central United States. *Climate Dynamics*, **49** (11), 4293-4310. http://dx.doi.org/10.1007/s00382-017-3534-z

109. Cook, B.I., T.R. Ault, and J.E. Smerdon, 2015: Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Science Advances*, **1** (1), e1400082. http://dx.doi.org/10.1126/sciadv.1400082

110. Seager, R., M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, and N. Henderson, 2015: Causes of the 2011–14 California drought. *Journal of Climate*, **28** (18), 6997-7024. http://dx.doi.org/10.1175/JCLI-D-14-00860.1

111. Swain, S. and K. Hayhoe, 2015: CMIP5 projected changes in spring and summer drought and wet conditions over North America. *Climate Dynamics*, **44** (9), 2737-2750. http://dx.doi.org/10.1007/s00382-014-2255-9

112. Williams, A.P., R. Seager, J.T. Abatzoglou, B.I. Cook, J.E. Smerdon, and E.R. Cook, 2015: Contribution of anthropogenic warming to California drought during 2012–2014. *Geophysical Research Letters*, **42** (16), 6819-6828. http://dx.doi.org/10.1002/2015GL064924

113. McCabe, G.J., D.M. Wolock, and S.H. Austin, 2017: Variability of runoff-based drought conditions in the conterminous United States. *International Journal of Climatology*, **37** (2), 1014-1021. http://dx.doi.org/10.1002/joc.4756

114. IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, 582 pp. https://www.ipcc.ch/pdf/special-reports/srex/SREX_Full_Report.pdf

115. Williams, A.P., R. Seager, M. Berkelhammer, A.K. Macalady, M.A. Crimmins, T.W. Swetnam, A.T. Trugman, N. Buenning, N. Hryniw, N.G. McDowell, D. Noone, C.I. Mora, and T. Rahn, 2014: Causes and implications of extreme atmospheric moisture demand during the record-breaking 2011 wildfire season in the southwestern United States. *Journal of Applied Meteorology and Climatology*, **53** (12), 2671-2684. http://dx.doi.org/10.1175/jamc-d-14-0053.1

116. Jeong, D.I. and L. Sushama, 2017: Rain-on-snow events over North America based on two Canadian regional climate models. *Climate Dynamics*. http://dx.doi.org/10.1007/s00382-017-3609-x

117. Serreze, M.C., A.P. Barrett, J.C. Stroeve, D.N. Kindig, and M.M. Holland, 2009: The emergence of surface-based Arctic amplification. *The Cryosphere*, **3** (1), 11-19. http://dx.doi.org/10.5194/tc-3-11-2009

118. Bekryaev, R.V., I.V. Polyakov, and V.A. Alexeev, 2010: Role of polar amplification in long-term surface air temperature variations and modern Arctic warming. *Journal of Climate*, **23** (14), 3888-3906. http://dx.doi.org/10.1175/2010jcli3297.1

119. Screen, J.A. and I. Simmonds, 2010: The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, **464** (7293), 1334-1337. http://dx.doi.org/10.1038/nature09051

120. Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild, and P.M. Zhai, 2013: Observations: Atmosphere and surface. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 159–254. http://www.climatechange2013.org/report/full-report/

121. Overland, J., E. Hanna, I. Hanssen-Bauer, S.-J. Kim, J. Walsh, M. Wang, and U. Bhatt, 2014: Air Temperature [in Arctic Report Card 2014]. ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard_full_report2014.pdf

122. Taylor, P.C., W. Maslowski, J. Perlwitz, and D.J. Wuebbles, 2017: Arctic changes and their effects on Alaska and the rest of the United States. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 303-332. http://dx.doi.org/10.7930/J00863GK

123. AMAP, 2017: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 269 pp. https://www.amap.no/documents/doc/Snow-Water-Ice-and-Permafrost-in-the-Arctic-SWIPA-2017/1610

124. Schaefer, K., H. Lantuit, E.R. Vladimir, E.A.G. Schuur, and R. Witt, 2014: The impact of the permafrost carbon feedback on global climate. *Environmental Research Letters*, **9** (8), 085003. http://dx.doi.org/10.1088/1748-9326/9/8/085003

125. Koven, C.D., E.A.G. Schuur, C. Schädel, T.J. Bohn, E.J. Burke, G. Chen, X. Chen, P. Ciais, G. Grosse, J.W. Harden, D.J. Hayes, G. Hugelius, E.E. Jafarov, G. Krinner, P. Kuhry, D.M. Lawrence, A.H. MacDougall, S.S. Marchenko, A.D. McGuire, S.M. Natali, D.J. Nicolsky, D. Olefeldt, S. Peng, V.E. Romanovsky, K.M. Schaefer, J. Strauss, C.C. Treat, and M. Turetsky, 2015: A simplified, data-constrained approach to estimate the permafrost carbon–climate feedback. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **373** (2054), 20140423. http://dx.doi.org/10.1098/rsta.2014.0423

126. Schuur, E.A.G., A.D. McGuire, C. Schadel, G. Grosse, J.W. Harden, D.J. Hayes, G. Hugelius, C.D. Koven, P. Kuhry, D.M. Lawrence, S.M. Natali, D. Olefeldt, V.E. Romanovsky, K. Schaefer, M.R. Turetsky, C.C. Treat, and J.E. Vonk, 2015: Climate change and the permafrost carbon feedback. *Nature*, **520** (7546), 171-179. http://dx.doi.org/10.1038/nature14338

127. Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen, and T. Zhang, 2013: Observations: Cryosphere. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 317–382. http://www.climatechange2013.org/report/full-report/

128. Zemp, M., H. Frey, I. Gärtner-Roer, S.U. Nussbaumer, M. Hoelzle, F. Paul, W. Haeberli, F. Denzinger, A.P. Ahlstrøm, B. Anderson, S. Bajracharya, C. Baroni, L.N. Braun, B.E. Cáceres, G. Casassa, G. Cobos, L.R. Dávila, H. Delgado Granados, M.N. Demuth, L. Espizua, A. Fischer, K. Fujita, B. Gadek, A. Ghazanfar, J.O. Hagen, P. Holmlund, N. Karimi, Z. Li, M. Pelto, P. Pitte, V.V. Popovnin, C.A. Portocarrero, R. Prinz, C.V. Sangewar, I. Severskiy, O. Sigurðsson, A. Soruco, R. Usubaliev, and C. Vincent, 2015: Historically unprecedented global glacier decline in the early 21st century. *Journal of Glaciology*, **61** (228), 745-762. http://dx.doi.org/10.3189/2015JoG15J017

129. AMAP, 2011: *Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere*. Arctic Monitoring and Assessment Programme, Oslo, Norway, 538 pp. http://www.amap.no/documents/download/968

130. Pelto, M.S., 2015: [Global climate] Alpine glaciers [in "State of the Climate in 2014"]. *Bulletin of the American Meteorological Society*, **96 (12)** (7), S19-S20. http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

131. Harig, C. and F.J. Simons, 2016: Ice mass loss in Greenland, the Gulf of Alaska, and the Canadian Archipelago: Seasonal cycles and decadal trends. *Geophysical Research Letters*, **43** (7), 3150-3159. http://dx.doi.org/10.1002/2016GL067759

132. Joughin, I., S.B. Das, M.A. King, B.E. Smith, I.M. Howat, and T. Moon, 2008: Seasonal speedup along the western flank of the Greenland Ice Sheet. *Science*, **320** (5877), 781-783. http://dx.doi.org/10.1126/science.1153288

133. Holland, D.M., R.H. Thomas, B. de Young, M.H. Ribergaard, and B. Lyberth, 2008: Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nature Geoscience*, **1** (10), 659-664. http://dx.doi.org/10.1038/ngeo316

134. Rignot, E., M. Koppes, and I. Velicogna, 2010: Rapid submarine melting of the calving faces of West Greenland glaciers. *Nature Geoscience*, **3** (3), 187-191. http://dx.doi.org/10.1038/ngeo765

135. Bartholomew, I.D., P. Nienow, A. Sole, D. Mair, T. Cowton, M.A. King, and S. Palmer, 2011: Seasonal variations in Greenland Ice Sheet motion: Inland extent and behaviour at higher elevations. *Earth and Planetary Science Letters*, **307** (3–4), 271-278. http://dx.doi.org/10.1016/j.epsl.2011.04.014

136. Comiso, J.C. and D.K. Hall, 2014: Climate trends in the Arctic as observed from space. *Wiley Interdisciplinary Reviews: Climate Change*, **5** (3), 389-409. http://dx.doi.org/10.1002/wcc.277

137. Tschudi, M., C. Fowler, J. Maslanik, J.S. Stewart, and W. Meier. 2016: EASE-Grid Sea Ice Age, Version 3. NASA, National Snow and Ice Data Center Distributed Active Archive Center. http://dx.doi.org/10.5067/PFSVFZA9Y85G

138. Abe, M., T. Nozawa, T. Ogura, and K. Takata, 2016: Effect of retreating sea ice on Arctic cloud cover in simulated recent global warming. *Atmospheric Chemistry Physics*, **16** (22), 14343-14356. http://dx.doi.org/10.5194/acp-16-14343-2016

139. Pedersen, R.A., I. Cvijanovic, P.L. Langen, and B.M. Vinther, 2016: The impact of regional arctic sea ice loss on atmospheric circulation and the NAO. *Journal of Climate*, **29** (2), 889-902. http://dx.doi.org/10.1175/jcli-d-15-0315.1

140. Post, E., U.S. Bhatt, C.M. Bitz, J.F. Brodie, T.L. Fulton, M. Hebblewhite, J. Kerby, S.J. Kutz, I. Stirling, and D.A. Walker, 2013: Ecological consequences of sea-ice decline. *Science*, **341** (6145), 519-24. http://dx.doi.org/10.1126/science.1235225

141. Barnhart, K.R., I. Overeem, and R.S. Anderson, 2014: The effect of changing sea ice on the physical vulnerability of Arctic coasts. *The Cryosphere*, **8** (5), 1777-1799. http://dx.doi.org/10.5194/tc-8-1777-2014

142. Vinnikov, K.Y., A. Robock, R.J. Stouffer, J.E. Walsh, C.L. Parkinson, D.J. Cavalieri, J.F.B. Mitchell, D. Garrett, and V.F. Zakharov, 1999: Global warming and Northern Hemisphere sea ice extent. *Science*, **286** (5446), 1934-1937. http://dx.doi.org/10.1126/science.286.5446.1934

143. Stroeve, J., M.M. Holland, W. Meier, T. Scambos, and M. Serreze, 2007: Arctic sea ice decline: Faster than forecast. *Geophysical Research Letters*, **34** (9), L09501. http://dx.doi.org/10.1029/2007GL029703

144. Min, S.-K., X. Zhang, and F. Zwiers, 2008: Human-induced Arctic moistening. *Science*, **320** (5875), 518-520. http://dx.doi.org/10.1126/science.1153468

145. Kay, J.E., M.M. Holland, and A. Jahn, 2011: Inter-annual to multi-decadal Arctic sea ice extent trends in a warming world. *Geophysical Research Letters*, **38** (15), L15708. http://dx.doi.org/10.1029/2011GL048008

146. Day, J.J., J.C. Hargreaves, J.D. Annan, and A. Abe-Ouchi, 2012: Sources of multi-decadal variability in Arctic sea ice extent. *Environmental Research Letters*, **7** (3), 034011. http://dx.doi.org/10.1088/1748-9326/7/3/034011

147. Wang, M. and J.E. Overland, 2012: A sea ice free summer Arctic within 30 years: An update from CMIP5 models. *Geophysical Research Letters*, **39** (18), L18501. http://dx.doi.org/10.1029/2012GL052868

148. Notz, D. and J. Marotzke, 2012: Observations reveal external driver for Arctic sea-ice retreat. *Geophysical Research Letters*, **39** (8), L08502. http://dx.doi.org/10.1029/2012GL051094

149. Snape, T.J. and P.M. Forster, 2014: Decline of Arctic sea ice: Evaluation and weighting of CMIP5 projections. *Journal of Geophysical Research Atmospheres*, **119** (2), 546-554. http://dx.doi.org/10.1002/2013JD020593

150. Delworth, T.L., F. Zeng, G.A. Vecchi, X. Yang, L. Zhang, and R. Zhang, 2016: The North Atlantic Oscillation as a driver of rapid climate change in the Northern Hemisphere. *Nature Geoscience*, **9** (7), 509-512. http://dx.doi.org/10.1038/ngeo2738

151. Wang, X.L., Y. Feng, G.P. Compo, V.R. Swail, F.W. Zwiers, R.J. Allan, and P.D. Sardeshmukh, 2012: Trends and low frequency variability of extra-tropical cyclone activity in the ensemble of twentieth century reanalysis. *Climate Dynamics*, **40** (11-12), 2775-2800. http://dx.doi.org/10.1007/s00382-012-1450-9

152. Vose, R.S., S. Applequist, M.A. Bourassa, S.C. Pryor, R.J. Barthelmie, B. Blanton, P.D. Bromirski, H.E. Brooks, A.T. DeGaetano, R.M. Dole, D.R. Easterling, R.E. Jensen, T.R. Karl, R.W. Katz, K. Klink, M.C. Kruk, K.E. Kunkel, M.C. MacCracken, T.C. Peterson, K. Shein, B.R. Thomas, J.E. Walsh, X.L. Wang, M.F. Wehner, D.J. Wuebbles, and R.S. Young, 2014: Monitoring and understanding changes in extremes: Extratropical storms, winds, and waves. *Bulletin of the American Meteorological Society*, **95** (3), 377-386. http://dx.doi.org/10.1175/BAMS-D-12-00162.1

153. Perlwitz, J., T. Knutson, J.P. Kossin, and A.N. LeGrande, 2017: Large-scale circulation and climate variability. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 161-184. http://dx.doi.org/10.7930/J0RV0KVQ

154. Colle, B.A., Z. Zhang, K.A. Lombardo, E. Chang, P. Liu, and M. Zhang, 2013: Historical evaluation and future prediction of eastern North American and western Atlantic extratropical cyclones in the CMIP5 models during the cool season. *Journal of Climate*, **26** (18), 6882-6903. http://dx.doi.org/10.1175/JCLI-D-12-00498.1

155. Francis, J. and N. Skific, 2015: Evidence linking rapid Arctic warming to mid-latitude weather patterns. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **373** (2045), 20140170. http://dx.doi.org/10.1098/rsta.2014.0170

156. Cohen, J., K. Pfeiffer, and J.A. Francis, 2018: Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States. *Nature Communications*, **9** (1), 869. http://dx.doi.org/10.1038/s41467-018-02992-9

157. Mann, M.E., S. Rahmstorf, K. Kornhuber, B.A. Steinman, S.K. Miller, and D. Coumou, 2017: Influence of anthropogenic climate change on planetary wave resonance and extreme weather events. *Scientific Reports*, **7**, 45242. http://dx.doi.org/10.1038/srep45242

158. Barnes, E.A. and L.M. Polvani, 2015: CMIP5 projections of arctic amplification, of the North American/North Atlantic circulation, and of their relationship. *Journal of Climate*, **28** (13), 5254-5271. http://dx.doi.org/10.1175/jcli-d-14-00589.1

159. Perlwitz, J., M. Hoerling, and R. Dole, 2015: Arctic tropospheric warming: Causes and linkages to lower latitudes. *Journal of Climate*, **28** (6), 2154-2167. http://dx.doi.org/10.1175/JCLI-D-14-00095.1

160. Screen, J.A., C. Deser, and L. Sun, 2015: Projected changes in regional climate extremes arising from Arctic sea ice loss. *Environmental Research Letters*, **10** (8), 084006. http://dx.doi.org/10.1088/1748-9326/10/8/084006

161. Lucas, C., B. Timbal, and H. Nguyen, 2014: The expanding tropics: A critical assessment of the observational and modeling studies. *Wiley Interdisciplinary Reviews: Climate Change*, **5** (1), 89-112. http://dx.doi.org/10.1002/wcc.251

162. Kossin, J.P., K.A. Emanuel, and G.A. Vecchi, 2014: The poleward migration of the location of tropical cyclone maximum intensity. *Nature*, **509** (7500), 349-352. http://dx.doi.org/10.1038/nature13278

163. Dettinger, M., 2011: Climate change, atmospheric rivers, and floods in California—A multimodel analysis of storm frequency and magnitude changes. *Journal of the American Water Resources Association*, **47** (3), 514-523. http://dx.doi.org/10.1111/j.1752-1688.2011.00546.x

164. Warner, M.D., C.F. Mass, and E.P. Salathé Jr., 2015: Changes in winter atmospheric rivers along the North American West Coast in CMIP5 climate models. *Journal of Hydrometeorology*, **16** (1), 118-128. http://dx.doi.org/10.1175/JHM-D-14-0080.1

165. Gao, Y., J. Lu, L.R. Leung, Q. Yang, S. Hagos, and Y. Qian, 2015: Dynamical and thermodynamical modulations on future changes of landfalling atmospheric rivers over western North America. *Geophysical Research Letters*, **42** (17), 7179-7186. http://dx.doi.org/10.1002/2015GL065435

166. Christensen, J.H., K. Krishna Kumar, E. Aldrian, S.-I. An, I.F.A. Cavalcanti, M. de Castro, W. Dong, P. Goswami, A. Hall, J.K. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D.B. Stephenson, S.-P. Xie, and T. Zhou, 2013: Climate phenomena and their relevance for future regional climate change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1217–1308. http://www.climatechange2013.org/report/full-report/

167. Sobel, A.H., S.J. Camargo, T.M. Hall, C.-Y. Lee, M.K. Tippett, and A.A. Wing, 2016: Human influence on tropical cyclone intensity. *Science*, **353** (6296), 242-246. http://dx.doi.org/10.1126/science.aaf6574

168. Camargo, S.J., 2013: Global and regional aspects of tropical cyclone activity in the CMIP5 models. *Journal of Climate*, **26** (24), 9880-9902. http://dx.doi.org/10.1175/jcli-d-12-00549.1

169. Walsh, K.J.E., S.J. Camargo, G.A. Vecchi, A.S. Daloz, J. Elsner, K. Emanuel, M. Horn, Y.-K. Lim, M. Roberts, C. Patricola, E. Scoccimarro, A.H. Sobel, S. Strazzo, G. Villarini, M. Wehner, M. Zhao, J.P. Kossin, T. LaRow, K. Oouchi, S. Schubert, H. Wang, J. Bacmeister, P. Chang, F. Chauvin, C. Jablonowski, A. Kumar, H. Murakami, T. Ose, K.A. Reed, R. Saravanan, Y. Yamada, C.M. Zarzycki, P.L. Vidale, J.A. Jonas, and N. Henderson, 2015: Hurricanes and climate: The U.S. CLIVAR Working Group on Hurricanes. *Bulletin of the American Meteorological Society*, **96 (12)** (6), 997-1017. http://dx.doi.org/10.1175/BAMS-D-13-00242.1

170. Knutson, T.R., J.J. Sirutis, M. Zhao, R.E. Tuleya, M. Bender, G.A. Vecchi, G. Villarini, and D. Chavas, 2015: Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. *Journal of Climate*, **28** (18), 7203-7224. http://dx.doi.org/10.1175/JCLI-D-15-0129.1

171. Wehner, M.F., K.A. Reed, B. Loring, D. Stone, and H. Krishnan, 2018: Changes in tropical cyclones under stabilized 1.5 and 2.0 °C global warming scenarios as simulated by the Community Atmospheric Model under the HAPPI protocols. *Earth System Dynamics*, **9** (1), 187-195. http://dx.doi.org/10.5194/esd-9-187-2018

172. Kossin, J.P., T. Hall, T. Knutson, K.E. Kunkel, R.J. Trapp, D.E. Waliser, and M.F. Wehner, 2017: Extreme storms. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 257-276. http://dx.doi.org/10.7930/J07S7KXX

173. Kunkel, K.E., T.R. Karl, H. Brooks, J. Kossin, J. Lawrimore, D. Arndt, L. Bosart, D. Changnon, S.L. Cutter, N. Doesken, K. Emanuel, P.Y. Groisman, R.W. Katz, T. Knutson, J. O'Brien, C.J. Paciorek, T.C. Peterson, K. Redmond, D. Robinson, J. Trapp, R. Vose, S. Weaver, M. Wehner, K. Wolter, and D. Wuebbles, 2013: Monitoring and understanding trends in extreme storms: State of knowledge. *Bulletin of the American Meteorological Society*, **94** (4), 499–514. http://dx.doi.org/10.1175/BAMS-D-11-00262.1

174. Smith, A.B. and R.W. Katz, 2013: U.S. billion-dollar weather and climate disasters: Data sources, trends, accuracy and biases. *Natural Hazards*, **67** (2), 387-410. http://dx.doi.org/10.1007/s11069-013-0566-5

175. Trapp, R.J., N.S. Diffenbaugh, H.E. Brooks, M.E. Baldwin, E.D. Robinson, and J.S. Pal, 2007: Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. *Proceedings of the National Academy of Sciences of the United States of America*, **104** (50), 19719-19723. http://dx.doi.org/10.1073/pnas.0705494104

176. Brooks, H.E., 2013: Severe thunderstorms and climate change. *Atmospheric Research*, **123**, 129-138. http://dx.doi.org/10.1016/j.atmosres.2012.04.002

177. Diffenbaugh, N.S., M. Scherer, and R.J. Trapp, 2013: Robust increases in severe thunderstorm environments in response to greenhouse forcing. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (41), 16361-16366. http://dx.doi.org/10.1073/pnas.1307758110

178. Rahmstorf, S., J.E. Box, G. Feulner, M.E. Mann, A. Robinson, S. Rutherford, and E.J. Schaffernicht, 2015: Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change*, **5** (5), 475-480. http://dx.doi.org/10.1038/nclimate2554

179. Yang, Q., T.H. Dixon, P.G. Myers, J. Bonin, D. Chambers, and M.R. van den Broeke, 2016: Recent increases in Arctic freshwater flux affects Labrador Sea convection and Atlantic overturning circulation. *Nature Communications*, **7**, 10525. http://dx.doi.org/10.1038/ncomms10525

180. Liu, W., S.-P. Xie, Z. Liu, and J. Zhu, 2017: Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. *Science Advances*, **3** (1), e1601666. http://dx.doi.org/10.1126/sciadv.1601666

181. Sévellec, F., A.V. Fedorov, and W. Liu, 2017: Arctic sea-ice decline weakens the Atlantic Meridional Overturning Circulation. *Nature Climate Change*, **7**, 604-610. http://dx.doi.org/10.1038/nclimate3353

182. Buckley, M.W. and J. Marshall, 2016: Observations, inferences, and mechanisms of the Atlantic Meridional Overturning Circulation: A review. *Reviews of Geophysics*, **54** (1), 5-63. http://dx.doi.org/10.1002/2015RG000493

183. Caesar, L., S. Rahmstorf, A. Robinson, G. Feulner, and V. Saba, 2018: Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, **556** (7700), 191-196. http://dx.doi.org/10.1038/s41586-018-0006-5

184. Thornalley, D.J.R., D.W. Oppo, P. Ortega, J.I. Robson, C.M. Brierley, R. Davis, I.R. Hall, P. Moffa-Sanchez, N.L. Rose, P.T. Spooner, I. Yashayaev, and L.D. Keigwin, 2018: Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years. *Nature*, **556** (7700), 227-230. http://dx.doi.org/10.1038/s41586-018-0007-4

185. Bakker, P., A. Schmittner, J.T.M. Lenaerts, A. Abe-Ouchi, D. Bi, M.R. Broeke, W.L. Chan, A. Hu, R.L. Beadling, S.J. Marsland, S.H. Mernild, O.A. Saenko, D. Swingedouw, A. Sullivan, and J. Yin, 2016: Fate of the Atlantic Meridional Overturning Circulation: Strong decline under continued warming and Greenland melting. *Geophysical Research Letters*, **43** (23), 12,252-12,260. http://dx.doi.org/10.1002/2016GL070457

186. Sweet, W., J. Park, J. Marra, C. Zervas, and S. Gill, 2014: Sea Level Rise and Nuisance Flood Frequency Changes Around the United States. NOAA Technical Report NOS CO-OPS 073. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 58 pp. http://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_073.pdf

187. Sweet, W.V. and J. Park, 2014: From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future*, **2** (12), 579-600. http://dx.doi.org/10.1002/2014EF000272

188. Ezer, T. and L.P. Atkinson, 2014: Accelerated flooding along the U.S. East Coast: On the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic Oscillations. *Earth's Future*, **2** (8), 362-382. http://dx.doi.org/10.1002/2014EF000252

189. Sweet, W., G. Dusek, J. Obeysekera, and J.J. Marra, 2018: Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold. NOAA Technical Report NOS CO-OPS 086. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 44 pp. https://tidesandcurrents.noaa.gov/publications/techrpt86_PaP_of_HTFlooding.pdf

190. Knutson, T.R., J.J. Sirutis, G.A. Vecchi, S. Garner, M. Zhao, H.-S. Kim, M. Bender, R.E. Tuleya, I.M. Held, and G. Villarini, 2013: Dynamical downscaling projections of twenty-first-century Atlantic hurricane activity: CMIP3 and CMIP5 model-based scenarios. *Journal of Climate*, **27** (17), 6591-6617. http://dx.doi.org/10.1175/jcli-d-12-00539.1

191. Seki, O., G.L. Foster, D.N. Schmidt, A. Mackensen, K. Kawamura, and R.D. Pancost, 2010: Alkenone and boron-based Pliocene pCO2 records. *Earth and Planetary Science Letters*, **292** (1–2), 201-211. http://dx.doi.org/10.1016/j.epsl.2010.01.037

192. Bowen, G.J., B.J. Maibauer, M.J. Kraus, U. Rohl, T. Westerhold, A. Steimke, P.D. Gingerich, S.L. Wing, and W.C. Clyde, 2015: Two massive, rapid releases of carbon during the onset of the Palaeocene-Eocene thermal maximum. *Nature Geoscience*, **8** (1), 44-47. http://dx.doi.org/10.1038/ngeo2316

193. Kirtland Turner, S., P.F. Sexton, C.D. Charles, and R.D. Norris, 2014: Persistence of carbon release events through the peak of early Eocene global warmth. *Nature Geoscience*, **7** (10), 748-751. http://dx.doi.org/10.1038/ngeo2240

194. Penman, D.E., B. Hönisch, R.E. Zeebe, E. Thomas, and J.C. Zachos, 2014: Rapid and sustained surface ocean acidification during the Paleocene-Eocene Thermal Maximum. *Paleoceanography*, **29** (5), 357-369. http://dx.doi.org/10.1002/2014PA002621

195. Crowley, T.J., 1990: Are there any satisfactory geologic analogs for a future greenhouse warming? *Journal of Climate*, **3** (11), 1282-1292. http://dx.doi.org/10.1175/1520-0442(1990)003<1282:atasga>2.0.co;2

196. Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S. Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason, and M. Rummukainen, 2013: Evaluation of climate models. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 741–866. http://www.climatechange2013.org/report/full-report/

197. Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber, 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **105** (6), 1786-1793. http://dx.doi.org/10.1073/pnas.0705414105

198. Kopp, R.E., R.L. Shwom, G. Wagner, and J. Yuan, 2016: Tipping elements and climate–economic shocks: Pathways toward integrated assessment. *Earth's Future*, **4**, 346-372. http://dx.doi.org/10.1002/2016EF000362

199. Caballero, R. and M. Huber, 2013: State-dependent climate sensitivity in past warm climates and its implications for future climate projections. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (35), 14162-14167. http://dx.doi.org/10.1073/pnas.1303365110

200. Laepple, T. and P. Huybers, 2014: Ocean surface temperature variability: Large model–data differences at decadal and longer periods. *Proceedings of the National Academy of Sciences of the United States of America*, **111** (47), 16682-16687. http://dx.doi.org/10.1073/pnas.1412077111

201. Lunt, D.J., T. Dunkley Jones, M. Heinemann, M. Huber, A. LeGrande, A. Winguth, C. Loptson, J. Marotzke, C.D. Roberts, J. Tindall, P. Valdes, and C. Winguth, 2012: A model–data comparison for a multi-model ensemble of early Eocene atmosphere–ocean simulations: EoMIP. *Climate of the Past*, **8** (5), 1717-1736. http://dx.doi.org/10.5194/cp-8-1717-2012

202. Easterling, D.R. and M.F. Wehner, 2009: Is the climate warming or cooling? *Geophysical Research Letters*, **36** (8), L08706. http://dx.doi.org/10.1029/2009GL037810

203. Branstator, G. and H. Teng, 2012: Potential impact of initialization on decadal predictions as assessed for CMIP5 models. *Geophysical Research Letters*, **39** (12), L12703. http://dx.doi.org/10.1029/2012GL051974

204. Deser, C., R. Knutti, S. Solomon, and A.S. Phillips, 2012: Communication of the role of natural variability in future North American climate. *Nature Climate Change*, **2** (11), 775-779. http://dx.doi.org/10.1038/nclimate1562

205. Santer, B.D., C. Mears, C. Doutriaux, P. Caldwell, P.J. Gleckler, T.M.L. Wigley, S. Solomon, N.P. Gillett, D. Ivanova, T.R. Karl, J.R. Lanzante, G.A. Meehl, P.A. Stott, K.E. Taylor, P.W. Thorne, M.F. Wehner, and F.J. Wentz, 2011: Separating signal and noise in atmospheric temperature changes: The importance of timescale. *Journal of Geophysical Research*, **116** (D22105), 1-19. http://dx.doi.org/10.1029/2011JD016263

206. Conover, J.H., 1990: *The Blue Hill Meteorological Observatory: The First 100 Years, 1885–1985*. American Meteorological Society, Boston, MA, 514 pp.

207. Parker, D.E., T.P. Legg, and C.K. Folland, 1992: A new daily central England temperature series, 1772–1991. *International Journal of Climatology*, **12** (4), 317-342. http://dx.doi.org/10.1002/joc.3370120402

208. USGCRP, 2017: Climate Science Special Report: Fourth National Climate Assessment, Volume I. 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, 470 pp. http://dx.doi.org/10.7930/J0J964J6

209. Rupp, D.E., P.W. Mote, N. Massey, C.J. Rye, R. Jones, and M.R. Allen, 2012: Did human influence on climate make the 2011 Texas drought more probable? [in "Explaining Extreme Events of 2011 from a Climate Perspective"]. *Bulletin of the American Meteorological Society*, **93** (7), 1052-1054. http://dx.doi.org/10.1175/BAMS-D-12-00021.1

210. Hoerling, M., M. Chen, R. Dole, J. Eischeid, A. Kumar, J.W. Nielsen-Gammon, P. Pegion, J. Perlwitz, X.-W. Quan, and T. Zhang, 2013: Anatomy of an extreme event. *Journal of Climate*, **26** (9), 2811–2832. http://dx.doi.org/10.1175/JCLI-D-12-00270.1

211. Jeon, S., C.J. Paciorek, and M.F. Wehner, 2016: Quantile-based bias correction and uncertainty quantification of extreme event attribution statements. *Weather and Climate Extremes*, **12**, 24-32. http://dx.doi.org/10.1016/j.wace.2016.02.001

212. Diffenbaugh, N.S., D.L. Swain, and D. Touma, 2015: Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (13), 3931-3936. http://dx.doi.org/10.1073/pnas.1422385112

213. Cheng, L., M. Hoerling, A. AghaKouchak, B. Livneh, X.-W. Quan, and J. Eischeid, 2016: How has human-induced climate change affected California drought risk? *Journal of Climate*, **29** (1), 111-120. http://dx.doi.org/10.1175/JCLI-D-15-0260.1

214. Knutson, T.R., F. Zeng, and A.T. Wittenberg, 2014: Seasonal and annual mean precipitation extremes occurring during 2013: A U.S. focused analysis [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society*, **95** (9), S19-S23. http://dx.doi.org/10.1175/1520-0477-95.9.S1.1

215. Angélil, O., D. Stone, M. Wehner, C.J. Paciorek, H. Krishnan, and W. Collins, 2017: An independent assessment of anthropogenic attribution statements for recent extreme temperature and rainfall events. *Journal of Climate*, **30**, 5-16. http://dx.doi.org/10.1175/JCLI-D-16-0077.1

216. Risser, M.D. and M.F. Wehner, 2017: Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. *Geophysical Research Letters*, **44** (24), 12,457-12,464. http://dx.doi.org/10.1002/2017GL075888

217. van Oldenborgh, G.J., K. van der Wiel, A. Sebastian, R. Singh, J. Arrighi, F. Otto, K. Haustein, S. Li, G. Vecchi, and H. Cullen, 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, **12** (12), 124009. http://dx.doi.org/10.1088/1748-9326/aa9ef2

218. Emanuel, K., 2017: Assessing the present and future probability of Hurricane Harvey's rainfall. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (48), 12681-12684. http://dx.doi.org/10.1073/pnas.1716222114

219. Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks, 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747-756. http://dx.doi.org/10.1038/nature08823

220. Hawkins, E. and R. Sutton, 2011: The potential to narrow uncertainty in projections of regional precipitation change. *Climate Dynamics*, **37** (1), 407-418. http://dx.doi.org/10.1007/s00382-010-0810-6

221. Tans, P. and R. Keeling, 2017: Trends in Atmospheric Carbon Dioxide. Annual Mean Growth Rate of CO_2 at Mauna Loa. NOAA Earth System Research Laboratory. https://www.esrl.noaa.gov/gmd/ccgg/trends/gr.html

222. Raupach, M.R., G. Marland, P. Ciais, C. Le Quéré, J.G. Canadell, G. Klepper, and C.B. Field, 2007: Global and regional drivers of accelerating CO_2 emissions. *Proceedings of the National Academy of Sciences of the United States of America*, **104** (24), 10288-10293. http://dx.doi.org/10.1073/pnas.0700609104

223. Le Quéré, C., M.R. Raupach, J.G. Canadell, G. Marland, L. Bopp, P. Ciais, T.J. Conway, S.C. Doney, R.A. Feely, P. Foster, P. Friedlingstein, K. Gurney, R.A. Houghton, J.I. House, C. Huntingford, P.E. Levy, M.R. Lomas, J. Majkut, N. Metzl, J.P. Ometto, G.P. Peters, I.C. Prentice, J.T. Randerson, S.W. Running, J.L. Sarmiento, U. Schuster, S. Sitch, T. Takahashi, N. Viovy, G.R. van der Werf, and F.I. Woodward, 2009: Trends in the sources and sinks of carbon dioxide. *Nature Geoscience*, **2** (12), 831-836. http://dx.doi.org/10.1038/ngeo689

224. Jackson, R.B., J.G. Canadell, C. Le Quere, R.M. Andrew, J.I. Korsbakken, G.P. Peters, and N. Nakicenovic, 2016: Reaching peak emissions. *Nature Climate Change*, **6** (1), 7-10. http://dx.doi.org/10.1038/nclimate2892

225. Korsbakken, J.I., G.P. Peters, and R.M. Andrew, 2016: Uncertainties around reductions in China's coal use and CO_2 emissions. *Nature Climate Change*, **6** (7), 687-690. http://dx.doi.org/10.1038/nclimate2963

226. Peters, G.P., R.M. Andrew, J.G. Canadell, S. Fuss, R.B. Jackson, Jan I. Korsbakken, C. Le Quéré, and N. Nakicenovic, 2017: Key indicators to track current progress and future ambition of the Paris Agreement. *Nature Climate Change*, **7**, 118-122. http://dx.doi.org/10.1038/nclimate3202

227. Peters, G.P., C. Le Quéré, R.M. Andrew, J.G. Canadell, P. Friedlingstein, T. Ilyina, R.B. Jackson, F. Joos, J.I. Korsbakken, G.A. McKinley, S. Sitch, and P. Tans, 2017: Towards real-time verification of CO_2 emissions. *Nature Climate Change*, **7** (12), 848-850. http://dx.doi.org/10.1038/s41558-017-0013-9

228. Le Quéré, C., R.M. Andrew, P. Friedlingstein, S. Sitch, J. Pongratz, A.C. Manning, J.I. Korsbakken, G.P. Peters, J.G. Canadell, R.B. Jackson, T.A. Boden, P.P. Tans, O.D. Andrews, V.K. Arora, D.C.E. Bakker, L. Barbero, M. Becker, R.A. Betts, L. Bopp, F. Chevallier, L.P. Chini, P. Ciais, C.E. Cosca, J. Cross, K. Currie, T. Gasser, I. Harris, J. Hauck, V. Haverd, R.A. Houghton, C.W. Hunt, G. Hurtt, T. Ilyina, A.K. Jain, E. Kato, M. Kautz, R.F. Keeling, K. Klein Goldewijk, A. Körtzinger, P. Landschützer, N. Lefèvre, A. Lenton, S. Lienert, I. Lima, D. Lombardozzi, N. Metzl, F. Millero, P.M.S. Monteiro, D.R. Munro, J.E.M.S. Nabel, S.I. Nakaoka, Y. Nojiri, X.A. Padin, A. Peregon, B. Pfeil, D. Pierrot, B. Poulter, G. Rehder, J. Reimer, C. Rödenbeck, J. Schwinger, R. Séférian, I. Skjelvan, B.D. Stocker, H. Tian, B. Tilbrook, F.N. Tubiello, I.T. van der Laan-Luijkx, G.R. van der Werf, S. van Heuven, N. Viovy, N. Vuichard, A.P. Walker, A.J. Watson, A.J. Wiltshire, S. Zaehle, and D. Zhu, 2018: Global carbon budget 2017. *Earth System Science Data*, **10** (1), 405-448. http://dx.doi.org/10.5194/essd-10-405-2018

229. Millar, R.J., J.S. Fuglestvedt, P. Friedlingstein, J. Rogelj, M.J. Grubb, H.D. Matthews, R.B. Skeie, P.M. Forster, D.J. Frame, and M.R. Allen, 2017: Emission budgets and pathways consistent with limiting warming to 1.5 °C. *Nature Geoscience*, **10**, 741-747. http://dx.doi.org/10.1038/ngeo3031

230. Millar, R.J., J.S. Fuglestvedt, P. Friedlingstein, J. Rogelj, M.J. Grubb, H.D. Matthews, R.B. Skeie, P.M. Forster, D.J. Frame, and M.R. Allen, 2018: Author Correction: Emission budgets and pathways consistent with limiting warming to 1.5 °C. *Nature Geoscience*, **11** (6), 454-455. http://dx.doi.org/10.1038/s41561-018-0153-1

231. Rogelj, J., A. Popp, K.V. Calvin, G. Luderer, J. Emmerling, D. Gernaat, S. Fujimori, J. Strefler, T. Hasegawa, G. Marangoni, V. Krey, E. Kriegler, K. Riahi, D.P. van Vuuren, J. Doelman, L. Drouet, J. Edmonds, O. Fricko, M. Harmsen, P. Havlík, F. Humpenöder, E. Stehfest, and M. Tavoni, 2018: Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, **8** (4), 325-332. http://dx.doi.org/10.1038/s41558-018-0091-3

232. van Vuuren, D.P., S. Deetman, M.G.J. den Elzen, A. Hof, M. Isaac, K. Klein Goldewijk, T. Kram, A. Mendoza Beltran, E. Stehfest, and J. van Vliet, 2011: RCP2.6: Exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change*, **109** (1-2), 95-116. http://dx.doi.org/10.1007/s10584-011-0152-3

233. Raftery, A.E., A. Zimmer, D.M.W. Frierson, R. Startz, and P. Liu, 2017: Less than 2 °C warming by 2100 unlikely. *Nature Climate Change*, **7**, 637-641. http://dx.doi.org/10.1038/nclimate3352

234. Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J. Galloway, M. Heimann, C. Jones, C. Le Quéré, R.B. Myneni, S. Piao, and P. Thornton, 2013: Carbon and other biogeochemical cycles. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 465–570. http://www.climatechange2013.org/report/full-report/

235. Joos, F., R. Roth, J.S. Fuglestvedt, G.P. Peters, I.G. Enting, W. von Bloh, V. Brovkin, E.J. Burke, M. Eby, N.R. Edwards, T. Friedrich, T.L. Frölicher, P.R. Halloran, P.B. Holden, C. Jones, T. Kleinen, F.T. Mackenzie, K. Matsumoto, M. Meinshausen, G.K. Plattner, A. Reisinger, J. Segschneider, G. Shaffer, M. Steinacher, K. Strassmann, K. Tanaka, A. Timmermann, and A.J. Weaver, 2013: Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: A multi-model analysis. *Atmospheric Chemistry and Physics*, **13** (5), 2793-2825. http://dx.doi.org/10.5194/acp-13-2793-2013

236. Brewer, M.C. and C.F. Mass, 2016: Projected changes in western U.S. large-scale summer synoptic circulations and variability in CMIP5 models. *Journal of Climate*, **29** (16), 5965-5978. http://dx.doi.org/10.1175/jcli-d-15-0598.1

237. Tang, Q., X. Zhang, and J.A. Francis, 2014: Extreme summer weather in northern mid-latitudes linked to a vanishing cryosphere. *Nature Climate Change*, **4** (1), 45-50. http://dx.doi.org/10.1038/nclimate2065

238. Nielsen-Gammon, J.W., F. Zhang, A.M. Odins, and B. Myoung, 2005: Extreme rainfall in Texas: Patterns and predictability. *Physical Geography*, **26** (5), 340-364. http://dx.doi.org/10.2747/0272-3646.26.5.340

239. Tippett, M.K., 2014: Changing volatility of U.S. annual tornado reports. *Geophysical Research Letters*, **41** (19), 6956-6961. http://dx.doi.org/10.1002/2014GL061347

240. Elsner, J.B., S.C. Elsner, and T.H. Jagger, 2015: The increasing efficiency of tornado days in the United States. *Climate Dynamics*, **45** (3), 651-659. http://dx.doi.org/10.1007/s00382-014-2277-3

241. Brooks, H.E., G.W. Carbin, and P.T. Marsh, 2014: Increased variability of tornado occurrence in the United States. *Science*, **346** (6207), 349-352. http://dx.doi.org/10.1126/science.1257460

242. Allen, J.T. and M.K. Tippett, 2015: The Characteristics of United States Hail Reports: 1955-2014. *Electronic Journal of Severe Storms Meteorology*. http://www.ejssm.org/ojs/index.php/ejssm/article/viewArticle/149

243. Van Klooster, S.L. and P.J. Roebber, 2009: Surface-based convective potential in the contiguous United States in a business-as-usual future climate. *Journal of Climate*, **22** (12), 3317-3330. http://dx.doi.org/10.1175/2009JCLI2697.1

244. Gensini, V.A. and T.L. Mote, 2014: Estimations of hazardous convective weather in the United States using dynamical downscaling. *Journal of Climate*, **27** (17), 6581-6589. http://dx.doi.org/10.1175/JCLI-D-13-00777.1

245. Seeley, J.T. and D.M. Romps, 2015: The effect of global warming on severe thunderstorms in the United States. *Journal of Climate*, **28** (6), 2443-2458. http://dx.doi.org/10.1175/JCLI-D-14-00382.1

246. Sanderson, B.M. and M.F. Wehner, 2017: Appendix B: Model weighting strategy. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. 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, 436-442. http://dx.doi.org/10.7930/J06T0JS3

247. Pierce, D.W., D.R. Cayan, and B.L. Thrasher, 2014: Statistical downscaling using Localized Constructed Analogs (LOCA). *Journal of Hydrometeorology*, **15** (6), 2558-2585. http://dx.doi.org/10.1175/jhm-d-14-0082.1

248. Prein, A.F., G.J. Holland, R.M. Rasmussen, M.P. Clark, and M.R. Tye, 2016: Running dry: The U.S. Southwest's drift into a drier climate state. *Geophysical Research Letters*, **43** (3), 1272-1279. http://dx.doi.org/10.1002/2015GL066727

249. IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, 1535 pp. http://www.climatechange2013.org/report/

250. IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge. U.K, New York, NY, USA, 996 pp. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm

251. Talley, L.D., 2007: *Hydrographic Atlas of the World Ocean Circulation Experiment* (WOCE). *Volume 2: Pacific Ocean*. Sparrow, M., P. Chapman, and J. Gould, Eds. International WOCE Project Office, Southampton, UK, 327 pp. http://dx.doi.org/10.21976/C6WC77

252. Argo, 2000: Argo Float Data and Metadata. Sea Scientific Open Data Edition (SEANOE), Argo Global Data Assembly Centre (GDAC). http://dx.doi.org/10.17882/42182

253. Huang, B., V.F. Banzon, E. Freeman, J. Lawrimore, W. Liu, T.C. Peterson, T.M. Smith, P.W. Thorne, S.D. Woodruff, and H.-M. Zhang, 2015: Extended Reconstructed Sea Surface Temperature Version 4 (ERSST.v4). Part I: Upgrades and intercomparisons. *Journal of Climate*, **28** (3), 911-930. http://dx.doi.org/10.1175/JCLI-D-14-00006.1

254. Belkin, I., 2016: Chapter 5.2: Sea surface temperature trends in large marine ecosystems. *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, 101-109. http://wedocs.unep.org/bitstream/handle/20.500.11822/13456/UNEP_DEWA_TWAP%20VOLUME%204%20REPORT_FINAL_4_MAY.pdf?sequence=1&isAllowed=y,%20English%20-%20Summary

255. Schmidtko, S., L. Stramma, and M. Visbeck, 2017: Decline in global oceanic oxygen content during the past five decades. *Nature*, **542** (7641), 335-339. http://dx.doi.org/10.1038/nature21399

256. Church, J.A. and N.J. White, 2006: A 20th century acceleration in global sea-level rise. *Geophysical Research Letters*, **33** (1), L01602. http://dx.doi.org/10.1029/2005GL024826

257. Mengel, M., A. Levermann, K. Frieler, A. Robinson, B. Marzeion, and R. Winkelmann, 2016: Future sea level rise constrained by observations and long-term commitment. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (10), 2597-2602. http://dx.doi.org/10.1073/pnas.1500515113

258. Jackson, L.P. and S. Jevrejeva, 2016: A probabilistic approach to 21st century regional sea-level projections using RCP and High-end scenarios. *Global and Planetary Change*, **146**, 179-189. http://dx.doi.org/10.1016/j.gloplacha.2016.10.006

259. Bamber, J.L. and W.P. Aspinall, 2013: An expert judgement assessment of future sea level rise from the ice sheets. *Nature Climate Change*, **3** (4), 424-427. http://dx.doi.org/10.1038/nclimate1778

260. Miller, K.G., R.E. Kopp, B.P. Horton, J.V. Browning, and A.C. Kemp, 2013: A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast. *Earth's Future*, **1** (1), 3-18. http://dx.doi.org/10.1002/2013EF000135

261. Pfeffer, W.T., J.T. Harper, and S. O'Neel, 2008: Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science*, **321** (5894), 1340-1343. http://dx.doi.org/10.1126/science.1159099

262. Sriver, R.L., N.M. Urban, R. Olson, and K. Keller, 2012: Toward a physically plausible upper bound of sea-level rise projections. *Climatic Change*, **115** (3), 893-902. http://dx.doi.org/10.1007/s10584-012-0610-6

263. Karl, T.R., J.T. Melillo, and T.C. Peterson, Eds., 2009: *Global Climate Change Impacts in the United States*. Cambridge University Press, New York, NY, 189 pp. http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf

264. CCSP, 2006: *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*. Karl, T.R., S.J. Hassol, C.D. Miller, and W.L. Murray, Eds., *Synthesis and Assessment Product 1.1*. National Oceanic and Atmospheric Administration, Washington, DC, 164 pp. http://www.globalchange.gov/browse/reports/sap-11-temperature-trends-lower-atmosphere-steps-understanding-reconciling

265. Vose, R.S., S. Applequist, M.J. Menne, C.N. Williams, Jr., and P. Thorne, 2012: An intercomparison of temperature trends in the US Historical Climatology Network and recent atmospheric reanalyses. *Geophysical Research Letters*, **39** (10), 6. http://dx.doi.org/10.1029/2012GL051387

266. Spencer, R.W., J.R. Christy, and W.D. Braswell, 2017: UAH Version 6 global satellite temperature products: Methodology and results. *Asia-Pacific Journal of Atmospheric Sciences*, **53** (1), 121-130. http://dx.doi.org/10.1007/s13143-017-0010-y

267. Wahl, E.R. and J.E. Smerdon, 2012: Comparative performance of paleoclimate field and index reconstructions derived from climate proxies and noise-only predictors. *Geophysical Research Letters*, **39** (6), L06703. http://dx.doi.org/10.1029/2012GL051086

268. Menne, M.J., I. Durre, R.S. Vose, B.E. Gleason, and T.G. Houston, 2012: An overview of the Global Historical Climatology Network-daily database. *Journal of Atmospheric and Oceanic Technology*, **29** (7), 897-910. http://dx.doi.org/10.1175/JTECH-D-11-00103.1

269. Zhang, X., L. Alexander, G.C. Hegerl, P. Jones, A.K. Tank, T.C. Peterson, B. Trewin, and F.W. Zwiers, 2011: Indices for monitoring changes in extremes based on daily temperature and precipitation data. *Wiley Interdisciplinary Reviews: Climate Change*, **2** (6), 851-870. http://dx.doi.org/10.1002/wcc.147

270. Russo, S., A. Dosio, R.G. Graversen, J. Sillmann, H. Carrao, M.B. Dunbar, A. Singleton, P. Montagna, P. Barbola, and J.V. Vogt, 2014: Magnitude of extreme heat waves in present climate and their projection in a warming world. *Journal of Geophysical Research Atmospheres*, **119** (22), 12,500-12,512. http://dx.doi.org/10.1002/2014JD022098

271. Sun, L., K.E. Kunkel, L.E. Stevens, A. Buddenberg, J.G. Dobson, and D.R. Easterling, 2015: Regional Surface Climate Conditions in CMIP3 and CMIP5 for the United States: Differences, Similarities, and Implications for the U.S. National Climate Assessment. NOAA Technical Report NESDIS 144. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, 111 pp. http://dx.doi.org/10.7289/V5RB72KG

272. Easterling, D.R. and T.C. Peterson, 1995: A new method for detecting undocumented discontinuities in climatological time series. *International Journal of Climatology*, **15** (4), 369-377. http://dx.doi.org/10.1002/joc.3370150403

273. Menne, M.J. and C.N. Williams, Jr., 2009: Homogenization of temperature series via pairwise comparisons. *Journal of Climate*, **22** (7), 1700-1717. http://dx.doi.org/10.1175/2008JCLI2263.1

274. Easterling, D.R., T.C. Peterson, and T.R. Karl, 1996: On the development and use of homogenized climate datasets. *Journal of Climate*, **9** (6), 1429-1434. http://dx.doi.org/10.1175/1520-0442(1996)009<1429:Otdauo>2.0.CO;2

275. Kunkel, K.E., D.R. Easterling, K. Redmond, and K. Hubbard, 2003: Temporal variations of extreme precipitation events in the United States: 1895–2000. *Geophysical Research Letters*, **30** (17). http://dx.doi.org/10.1029/2003GL018052

276. Groisman, P.Y., R.W. Knight, T.R. Karl, D.R. Easterling, B. Sun, and J.H. Lawrimore, 2004: Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *Journal of Hydrometeorology*, **5** (1), 64-85. http://dx.doi.org/10.1175/1525-7541(2004)005<0064:CCOTHC>2.0.CO;2

277. Westra, S., L.V. Alexander, and F.W. Zwiers, 2013: Global increasing trends in annual maximum daily precipitation. *Journal of Climate*, **26** (11), 3904-3918. http://dx.doi.org/10.1175/JCLI-D-12-00502.1

278. Wendler, G., B. Moore, and K. Galloway, 2014: Strong temperature increase and shrinking sea ice in Arctic Alaska. *The Open Atmospheric Science Journal*, **8**, 7-15. http://dx.doi.org/10.2174/1874282301408010007

279. Manabe, S. and R.T. Wetherald, 1975: The effects of doubling the CO_2 concentration on the climate of a General Circulation Model. *Journal of the Atmospheric Sciences*, **32** (1), 3-15. http://dx.doi.org/10.1175/1520-0469(1975)032<0003:teodtc>2.0.co;2

280. Taylor, P.C., M. Cai, A. Hu, J. Meehl, W. Washington, and G.J. Zhang, 2013: A decomposition of feedback contributions to polar warming amplification. *Journal of Climate*, **26** (18), 7023-7043. http://dx.doi.org/10.1175/JCLI-D-12-00696.1

281. ACIA, 2005: Arctic Climate Impact Assessment. ACIA Secretariat and Cooperative Institute for Arctic Research. Press, C.U., 1042 pp. http://www.acia.uaf.edu/pages/scientific.html

282. Fisher, J.B., M. Sikka, W.C. Oechel, D.N. Huntzinger, J.R. Melton, C.D. Koven, A. Ahlström, M.A. Arain, I. Baker, J.M. Chen, P. Ciais, C. Davidson, M. Dietze, B. El-Masri, D. Hayes, C. Huntingford, A.K. Jain, P.E. Levy, M.R. Lomas, B. Poulter, D. Price, A.K. Sahoo, K. Schaefer, H. Tian, E. Tomelleri, H. Verbeeck, N. Viovy, R. Wania, N. Zeng, and C.E. Miller, 2014: Carbon cycle uncertainty in the Alaskan arctic. *Biogeosciences*, **11** (15), 4271-4288. http://dx.doi.org/10.5194/bg-11-4271-2014

283. Koven, C.D., D.M. Lawrence, and W.J. Riley, 2015: Permafrost carbon−climate feedback is sensitive to deep soil carbon decomposability but not deep soil nitrogen dynamics. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (12), 3752-3757. http://dx.doi.org/10.1073/pnas.1415123112

284. Schädel, C., M.K.F. Bader, E.A.G. Schuur, C. Biasi, R. Bracho, P. Capek, S. De Baets, K. Diakova, J. Ernakovich, C. Estop-Aragones, D.E. Graham, I.P. Hartley, C.M. Iversen, E. Kane, C. Knoblauch, M. Lupascu, P.J. Martikainen, S.M. Natali, R.J. Norby, J.A. O'Donnell, T.R. Chowdhury, H. Santruckova, G. Shaver, V.L. Sloan, C.C. Treat, M.R. Turetsky, M.P. Waldrop, and K.P. Wickland, 2016: Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. *Nature Climate Change*, **6** (10), 950-953. http://dx.doi.org/10.1038/nclimate3054

285. Liljedahl, A.K., J. Boike, R.P. Daanen, A.N. Fedorov, G.V. Frost, G. Grosse, L.D. Hinzman, Y. Iijma, J.C. Jorgenson, N. Matveyeva, M. Necsoiu, M.K. Raynolds, V.E. Romanovsky, J. Schulla, K.D. Tape, D.A. Walker, C.J. Wilson, H. Yabuki, and D. Zona, 2016: Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nature Geoscience*, **9** (4), 312-318. http://dx.doi.org/10.1038/ngeo2674

286. Romanovsky, V.E., S.L. Smith, K. Isaksen, N.I. Shiklomanov, D.A. Streletskiy, A.L. Kholodov, H.H. Christiansen, D.S. Drozdov, G.V. Malkova, and S.S. Marchenko, 2016: [The Arctic] Terrestrial permafrost [in "State of the Climate in 2015"]. *Bulletin of the American Meteorological Society*, **97** (8), S149-S152. http://dx.doi.org/10.1175/2016BAMSStateoftheClimate.1

287. Tarnocai, C., J.G. Canadell, E.A.G. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov, 2009: Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles*, **23** (2), GB2023. http://dx.doi.org/10.1029/2008GB003327

288. Hugelius, G., J. Strauss, S. Zubrzycki, J.W. Harden, E.A.G. Schuur, C.L. Ping, L. Schirrmeister, G. Grosse, G.J. Michaelson, C.D. Koven, J.A. O'Donnell, B. Elberling, U. Mishra, P. Camill, Z. Yu, J. Palmtag, and P. Kuhry, 2014: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences*, **11** (23), 6573-6593. http://dx.doi.org/10.5194/bg-11-6573-2014

289. Schuur, E.A.G., J.G. Vogel, K.G. Crummer, H. Lee, J.O. Sickman, and T.E. Osterkamp, 2009: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature*, **459** (7246), 556-559. http://dx.doi.org/10.1038/nature08031

290. Zona, D., B. Gioli, R. Commane, J. Lindaas, S.C. Wofsy, C.E. Miller, S.J. Dinardo, S. Dengel, C. Sweeney, A. Karion, R.Y.-W. Chang, J.M. Henderson, P.C. Murphy, J.P. Goodrich, V. Moreaux, A. Liljedahl, J.D. Watts, J.S. Kimball, D.A. Lipson, and W.C. Oechel, 2016: Cold season emissions dominate the Arctic tundra methane budget. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (1), 40-45. http://dx.doi.org/10.1073/pnas.1516017113

291. Chadburn, S.E., E.J. Burke, P.M. Cox, P. Friedlingstein, G. Hugelius, and S. Westermann, 2017: An observation-based constraint on permafrost loss as a function of global warming. *Nature Climate Change*, **7**, 340-344. http://dx.doi.org/10.1038/nclimate3262

292. Hollesen, J., H. Matthiesen, A.B. Møller, and B. Elberling, 2015: Permafrost thawing in organic Arctic soils accelerated by ground heat production. *Nature Climate Change*, **5** (6), 574-578. http://dx.doi.org/10.1038/nclimate2590

293. Oh, Y., B. Stackhouse, M.C.Y. Lau, X. Xu, A.T. Trugman, J. Moch, T.C. Onstott, C.J. Jørgensen, L. D'Imperio, B. Elberling, C.A. Emmerton, V.L. St. Louis, and D. Medvigy, 2016: A scalable model for methane consumption in Arctic mineral soils. *Geophysical Research Letters*, **43** (10), 5143-5150. http://dx.doi.org/10.1002/2016GL069049

294. Treat, C.C., S.M. Natali, J. Ernakovich, C.M. Iversen, M. Lupascu, A.D. McGuire, R.J. Norby, T. Roy Chowdhury, A. Richter, H. Šantrůčková, C. Schädel, E.A.G. Schuur, V.L. Sloan, M.R. Turetsky, and M.P. Waldrop, 2015: A pan-Arctic synthesis of CH_4 and CO_2 production from anoxic soil incubations. *Global Change Biology*, **21** (7), 2787-2803. http://dx.doi.org/10.1111/gcb.12875

295. Stroeve, J., A. Barrett, M. Serreze, and A. Schweiger, 2014: Using records from submarine, aircraft and satellites to evaluate climate model simulations of Arctic sea ice thickness. *The Cryosphere*, **8** (5), 1839-1854. http://dx.doi.org/10.5194/tc-8-1839-2014

296. Larsen, C.F., E. Burgess, A.A. Arendt, S. O'Neel, A.J. Johnson, and C. Kienholz, 2015: Surface melt dominates Alaska glacier mass balance. *Geophysical Research Letters*, **42** (14), 5902-5908. http://dx.doi.org/10.1002/2015GL064349

297. Perovich, D., W. Meier, M. Tschudi, S. Farrell, S. Gerland, S. Hendricks, T. Krumpen, and C. Hass, 2016: Sea ice [in Arctic Report Card 2016]. http://www.arctic.noaa.gov/Report-Card/Report-Card-2016/ArtMID/5022/ArticleID/286/Sea-Ice

298. Davis, N.A. and T. Birner, 2013: Seasonal to multidecadal variability of the width of the tropical belt. *Journal of Geophysical Research Atmospheres*, **118** (14), 7773-7787. http://dx.doi.org/10.1002/jgrd.50610

299. Feng, S. and Q. Fu, 2013: Expansion of global drylands under a warming climate. *Atmospheric Chemistry and Physics*, **13** (19), 10081-10094. http://dx.doi.org/10.5194/acp-13-10081-2013

300. Birner, T., S.M. Davis, and D.J. Seidel, 2014: The changing width of Earth's tropical belt. *Physcis Today*, **67** (12), 38-44. http://dx.doi.org/10.1063/PT.3.2620

301. Karnauskas, K.B. and C.C. Ummenhofer, 2014: On the dynamics of the Hadley circulation and subtropical drying. *Climate Dynamics*, **42** (9), 2259-2269. http://dx.doi.org/10.1007/s00382-014-2129-1

302. Garfinkel, C.I., D.W. Waugh, and L.M. Polvani, 2015: Recent Hadley cell expansion: The role of internal atmospheric variability in reconciling modeled and observed trends. *Geophysical Research Letters*, **42** (24), 10,824-10,831. http://dx.doi.org/10.1002/2015GL066942

303. Waugh, D.W., C.I. Garfinkel, and L.M. Polvani, 2015: Drivers of the recent tropical expansion in the Southern Hemisphere: Changing SSTs or ozone depletion? *Journal of Climate*, **28** (16), 6581-6586. http://dx.doi.org/10.1175/JCLI-D-15-0138.1

304. Norris, J.R., R.J. Allen, A.T. Evan, M.D. Zelinka, C.W. O'Dell, and S.A. Klein, 2016: Evidence for climate change in the satellite cloud record. *Nature*, **536** (7614), 72-75. http://dx.doi.org/10.1038/nature18273

305. Reichler, T., 2016: Chapter 6: Poleward expansion of the atmospheric circulation. *Climate Change (Second Edition)*. Letcher, T.M., Ed. Elsevier, Boston, 79-104. http://dx.doi.org/10.1016/B978-0-444-63524-2.00006-3

306. Barnes, E.A. and L. Polvani, 2013: Response of the midlatitude jets, and of their variability, to increased greenhouse gases in the CMIP5 models. *Journal of Climate*, **26** (18), 7117-7135. http://dx.doi.org/10.1175/JCLI-D-12-00536.1

307. Vallis, G.K., P. Zurita-Gotor, C. Cairns, and J. Kidston, 2015: Response of the large-scale structure of the atmosphere to global warming. *Quarterly Journal of the Royal Meteorological Society*, **141** (690), 1479-1501. http://dx.doi.org/10.1002/qj.2456

308. Allen, R.J., S.C. Sherwood, J.R. Norris, and C.S. Zender, 2012: Recent Northern Hemisphere tropical expansion primarily driven by black carbon and tropospheric ozone. *Nature*, **485** (7398), 350-354. http://dx.doi.org/10.1038/nature11097

309. Kovilakam, M. and S. Mahajan, 2015: Black carbon aerosol-induced Northern Hemisphere tropical expansion. *Geophysical Research Letters*, **42** (12), 4964-4972. http://dx.doi.org/10.1002/2015GL064559

310. Adam, O., T. Schneider, and N. Harnik, 2014: Role of changes in mean temperatures versus temperature gradients in the recent widening of the Hadley circulation. *Journal of Climate*, **27** (19), 7450-7461. http://dx.doi.org/10.1175/JCLI-D-14-00140.1

311. Allen, R.J., J.R. Norris, and M. Kovilakam, 2014: Influence of anthropogenic aerosols and the Pacific Decadal Oscillation on tropical belt width. *Nature Geoscience*, **7** (4), 270-274. http://dx.doi.org/10.1038/ngeo2091

312. Payne, A.E. and G. Magnusdottir, 2015: An evaluation of atmospheric rivers over the North Pacific in CMIP5 and their response to warming under RCP 8.5. *Journal of Geophysical Research Atmospheres*, **120** (21), 11,173-11,190. http://dx.doi.org/10.1002/2015JD023586

313. Radić, V., A.J. Cannon, B. Menounos, and N. Gi, 2015: Future changes in autumn atmospheric river events in British Columbia, Canada, as projected by CMIP5 global climate models. *Journal of Geophysical Research Atmospheres*, **120** (18), 9279-9302. http://dx.doi.org/10.1002/2015JD023279

314. Hagos, S.M., L.R. Leung, J.-H. Yoon, J. Lu, and Y. Gao, 2016: A projection of changes in landfalling atmospheric river frequency and extreme precipitation over western North America from the Large Ensemble CESM simulations. *Geophysical Research Letters*, **43** (3), 1357-1363. http://dx.doi.org/10.1002/2015GL067392

315. Guan, B., N.P. Molotch, D.E. Waliser, E.J. Fetzer, and P.J. Neiman, 2010: Extreme snowfall events linked to atmospheric rivers and surface air temperature via satellite measurements. *Geophysical Research Letters*, **37** (20), L20401. http://dx.doi.org/10.1029/2010GL044696

316. Ralph, F.M., P.J. Neiman, G.A. Wick, S.I. Gutman, M.D. Dettinger, D.R. Cayan, and A.B. White, 2006: Flooding on California's Russian River: Role of atmospheric rivers. *Geophysical Research Letters*, **33** (13), L13801. http://dx.doi.org/10.1029/2006GL026689

317. Neiman, P.J., L.J. Schick, F.M. Ralph, M. Hughes, and G.A. Wick, 2011: Flooding in western Washington: The connection to atmospheric rivers. *Journal of Hydrometeorology*, **12** (6), 1337-1358. http://dx.doi.org/10.1175/2011JHM1358.1

318. Moore, B.J., P.J. Neiman, F.M. Ralph, and F.E. Barthold, 2012: Physical processes associated with heavy flooding rainfall in Nashville, Tennessee, and vicinity during 1–2 May 2010: The role of an atmospheric river and mesoscale convective systems. *Monthly Weather Review*, **140** (2), 358-378. http://dx.doi.org/10.1175/MWR-D-11-00126.1

319. Dettinger, M.D., 2013: Atmospheric rivers as drought busters on the U.S. West Coast. *Journal of Hydrometeorology*, **14** (6), 1721-1732. http://dx.doi.org/10.1175/JHM-D-13-02.1

320. Kopp, R.E., C.C. Hay, C.M. Little, and J.X. Mitrovica, 2015: Geographic variability of sea-level change. *Current Climate Change Reports*, **1** (3), 192-204. http://dx.doi.org/10.7282/T37W6F4P

321. PSMSL, 2016: Obtaining Tide Gauge Data. Permanent Service for Mean Sea Level. http://www.psmsl.org/data/obtaining/

322. Holgate, S.J., A. Matthews, P.L. Woodworth, L.J. Rickards, M.E. Tamisiea, E. Bradshaw, P.R. Foden, K.M. Gordon, S. Jevrejeva, and J. Pugh, 2013: New data systems and products at the Permanent Service for Mean Sea Level. *Journal of Coastal Research*, **29** (3), 493-504. http://dx.doi.org/10.2112/JCOASTRES-D-12-00175.1

323. Engelhart, S.E. and B.P. Horton, 2012: Holocene sea level database for the Atlantic coast of the United States. *Quaternary Science Reviews*, **54**, 12-25. http://dx.doi.org/10.1016/j.quascirev.2011.09.013

324. Farrell, W.E. and J.A. Clark, 1976: On postglacial sea level. *Geophysical Journal International*, **46** (3), 647-667. http://dx.doi.org/10.1111/j.1365-246X.1976.tb01252.x

325. Mitrovica, J.X., N. Gomez, E. Morrow, C. Hay, K. Latychev, and M.E. Tamisiea, 2011: On the robustness of predictions of sea level fingerprints. *Geophysical Journal International*, **187** (2), 729-742. http://dx.doi.org/10.1111/j.1365-246X.2011.05090.x

326. Yin, J., M.E. Schlesinger, and R.J. Stouffer, 2009: Model projections of rapid sea-level rise on the northeast coast of the United States. *Nature Geoscience*, **2** (4), 262-266. http://dx.doi.org/10.1038/ngeo462

327. Yin, J. and P.B. Goddard, 2013: Oceanic control of sea level rise patterns along the East Coast of the United States. *Geophysical Research Letters*, **40** (20), 5514-5520. http://dx.doi.org/10.1002/2013GL057992

328. Tebaldi, C., B.H. Strauss, and C.E. Zervas, 2012: Modelling sea level rise impacts on storm surges along US coasts. *Environmental Research Letters*, **7** (1), 014032. http://dx.doi.org/10.1088/1748-9326/7/1/014032

329. Horton, R.M., V. Gornitz, D.A. Bader, A.C. Ruane, R. Goldberg, and C. Rosenzweig, 2011: Climate hazard assessment for stakeholder adaptation planning in New York City. *Journal of Applied Meteorology and Climatology*, **50** (11), 2247-2266. http://dx.doi.org/10.1175/2011JAMC2521.1

330. Woodruff, J.D., J.L. Irish, and S.J. Camargo, 2013: Coastal flooding by tropical cyclones and sea-level rise. *Nature*, **504** (7478), 44-52. http://dx.doi.org/10.1038/nature12855

331. Sweet, W.V., C. Zervas, S. Gill, and J. Park, 2013: Hurricane Sandy inundation probabilities of today and tomorrow [in "Explaining Extreme Events of 2012 from a Climate Perspective"]. *Bulletin of the American Meteorological Society*, **94 (9)**, S17-S20. http://dx.doi.org/10.1175/BAMS-D-13-00085.1

332. Buchanan, M.K., R.E. Kopp, M. Oppenheimer, and C. Tebaldi, 2016: Allowances for evolving coastal flood risk under uncertain local sea-level rise. *Climatic Change*, **137** (3), 347-362. http://dx.doi.org/10.1007/s10584-016-1664-7

333. Hall, J.A., S. Gill, J. Obeysekera, W. Sweet, K. Knuuti, and J. Marburger, 2016: Regional Sea Level Scenarios for Coastal Risk Management: Managing the Uncertainty of Future Sea Level Change and Extreme Water Levels for Department of Defense Coastal Sites Worldwide. U.S. Department of Defense, Strategic Environmental Research and Development Program, Alexandria VA, 224 pp. https://www.usfsp.edu/icar/files/2015/08/CARSWG-SLR-FINAL-April-2016.pdf

334. Grinsted, A., J.C. Moore, and S. Jevrejeva, 2013: Projected Atlantic hurricane surge threat from rising temperatures. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (14), 5369-5373. http://dx.doi.org/10.1073/pnas.1209980110

335. Lin, N., K. Emanuel, M. Oppenheimer, and E. Vanmarcke, 2012: Physically based assessment of hurricane surge threat under climate change. *Nature Climate Change*, **2** (6), 462-467. http://dx.doi.org/10.1038/nclimate1389

336. Little, C.M., R.M. Horton, R.E. Kopp, M. Oppenheimer, and S. Yip, 2015: Uncertainty in twenty-first-century CMIP5 sea level projections. *Journal of Climate*, **28** (2), 838-852. http://dx.doi.org/10.1175/JCLI-D-14-00453.1

337. Lin, N., R.E. Kopp, B.P. Horton, and J.P. Donnelly, 2016: Hurricane Sandy's flood frequency increasing from year 1800 to 2100. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (43), 12071-12075. http://dx.doi.org/10.1073/pnas.1604386113

338. Hall, T. and E. Yonekura, 2013: North American tropical cyclone landfall and SST: A statistical model study. *Journal of Climate*, **26** (21), 8422-8439. http://dx.doi.org/10.1175/jcli-d-12-00756.1

339. NRC, 2013: *Abrupt Impacts of Climate Change: Anticipating Surprises*. The National Academies Press, Washington, DC, 222 pp. http://dx.doi.org/10.17226/18373

340. Salzmann, U., A.M. Dolan, A.M. Haywood, W.-L. Chan, J. Voss, D.J. Hill, A. Abe-Ouchi, B. Otto-Bliesner, F.J. Bragg, M.A. Chandler, C. Contoux, H.J. Dowsett, A. Jost, Y. Kamae, G. Lohmann, D.J. Lunt, S.J. Pickering, M.J. Pound, G. Ramstein, N.A. Rosenbloom, L. Sohl, C. Stepanek, H. Ueda, and Z. Zhang, 2013: Challenges in quantifying Pliocene terrestrial warming revealed by data-model discord. *Nature Climate Change*, **3** (11), 969-974. http://dx.doi.org/10.1038/nclimate2008

341. Goldner, A., N. Herold, and M. Huber, 2014: The challenge of simulating the warmth of the mid-Miocene climatic optimum in CESM1. *Climate of the Past*, **10** (2), 523-536. http://dx.doi.org/10.5194/cp-10-523-2014