Executive Summary

Introduction

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

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

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

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

Global and U.S. Temperatures Continue to Rise

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

Changes in Observed and Projected Global Temperature

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

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

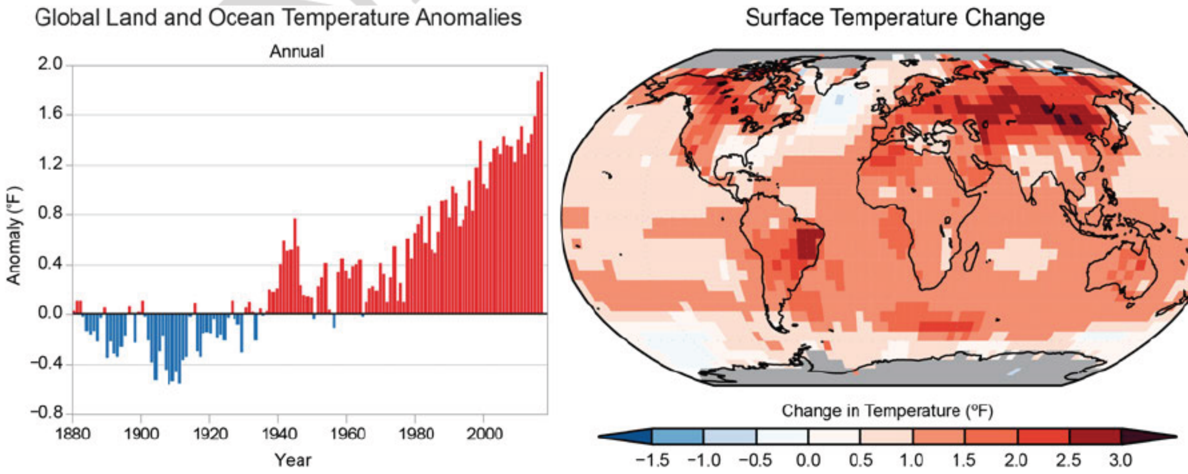


Figure ES.1 Global Temperatures Continue to Rise
Left: Global annual average temperature has increased by more than 1.2°F (0.7°C) for the period 1986–2016 relative to 1901–1960. Red bars show temperatures that were above the 1901–1960 average, and blue bars indicate temperatures below the average. Right: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

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

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

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

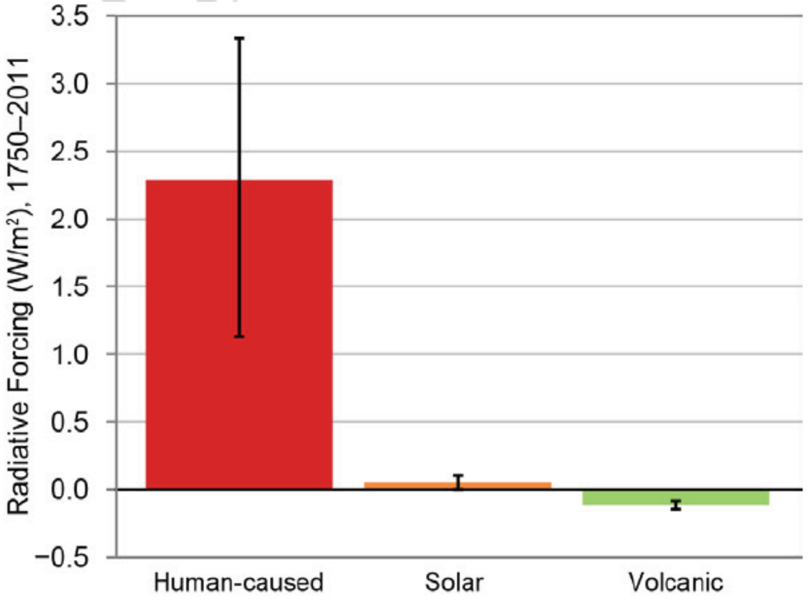


Figure ES.2 Human Activities Are the Primary Driver of Recent Global Temperature Rise

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

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

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

Sidebar: Scenarios Used in this Assessment

Projections of future climate conditions use a range of plausible future scenarios. Consistent with previous practice, this assessment relies on scenarios generated for the Intergovernmental Panel on Climate Change (IPCC). The IPCC completed its last assessment in 2013–2014, and its projections were based on updated scenarios, namely four “representative concentration pathways” (RCPs). The RCP scenarios are numbered according to changes in radiative forcing in 2100 relative to preindustrial conditions: +2.6, +4.5, +6.0 and +8.5 watts per square meter (W/m^2). Radiative forcing is a measure of the influence a factor (such as greenhouse gas emissions) has in changing the global balance of incoming and outgoing energy. Greenhouse gases (GHGs) in the atmosphere absorb most of the outgoing radiation, leading to a warming of the surface and atmosphere. Though multiple emissions pathways could lead to the same 2100 radiative forcing value, an associated pathway of CO_2 and other human-caused emissions of greenhouse gases, aerosols, and air pollutants has been selected for each RCP. RCP8.5 implies a future with continued high emissions growth, whereas the other RCPs represent different pathways of mitigating emissions. Figure ES.3 shows these emission pathways and the corresponding projected changes in global temperature.

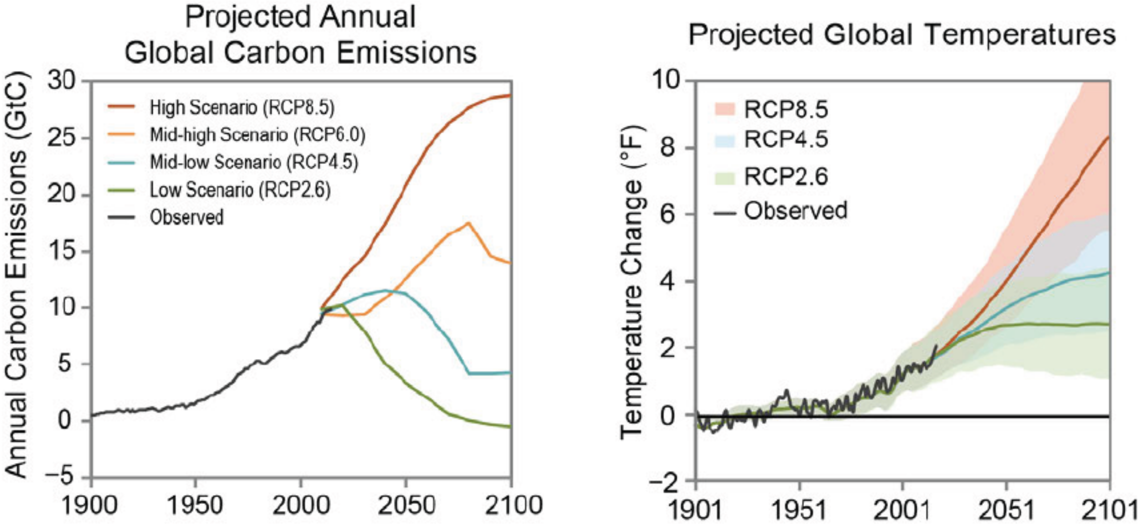


Figure ES.3. Greater Emissions Lead to Significantly More Warming. The two panels above show annual historical and a range of plausible future carbon emissions in units of gigatons of carbon (GtC) per year (left) and the historical observed and future temperature change that would result for a range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

Changes in Observed and Projected U.S. Temperature

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

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

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

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

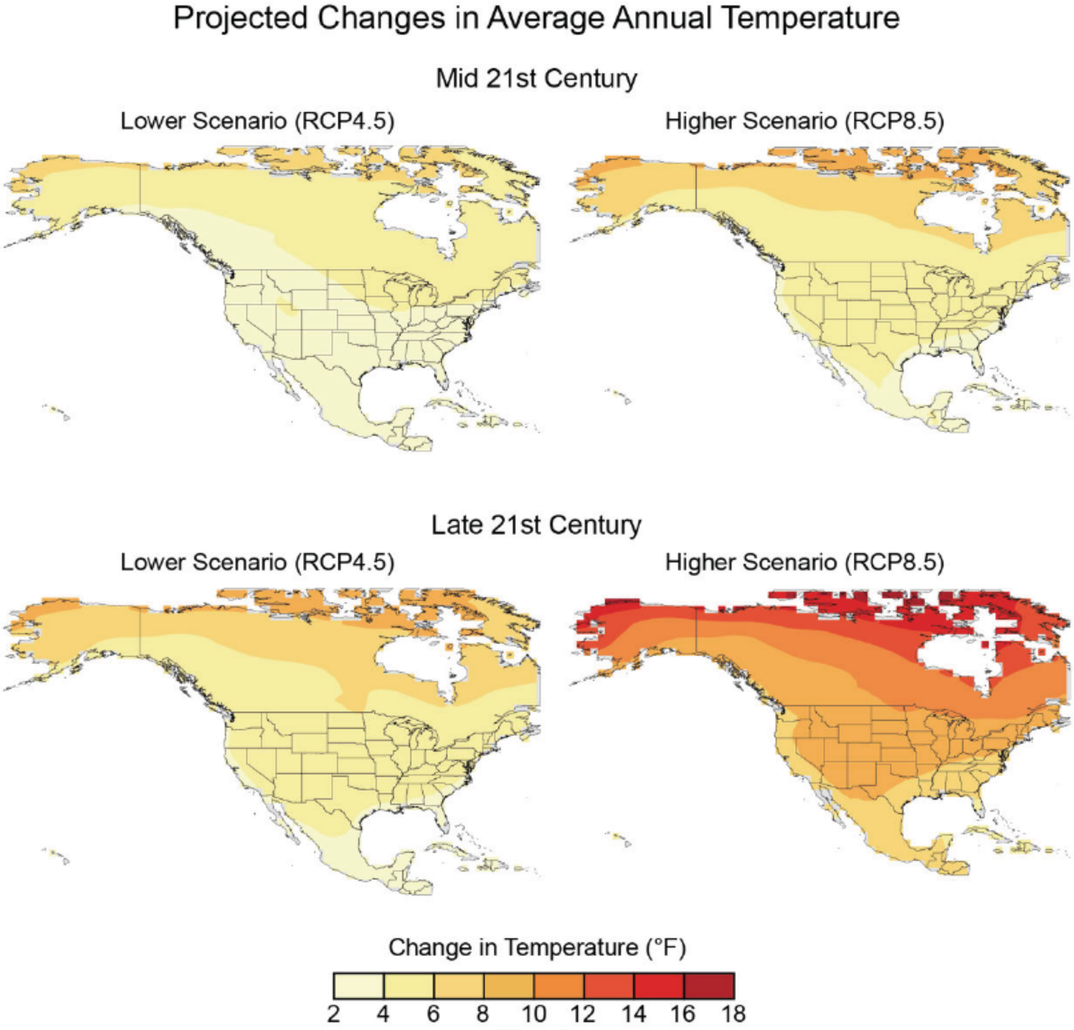


Figure ES.4 Significantly More Warming Occurs Under Higher Greenhouse Gas Concentration Scenarios

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

Many Temperature and Precipitation Extremes Are Becoming More Common

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

Observed Changes in Extremes

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

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

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

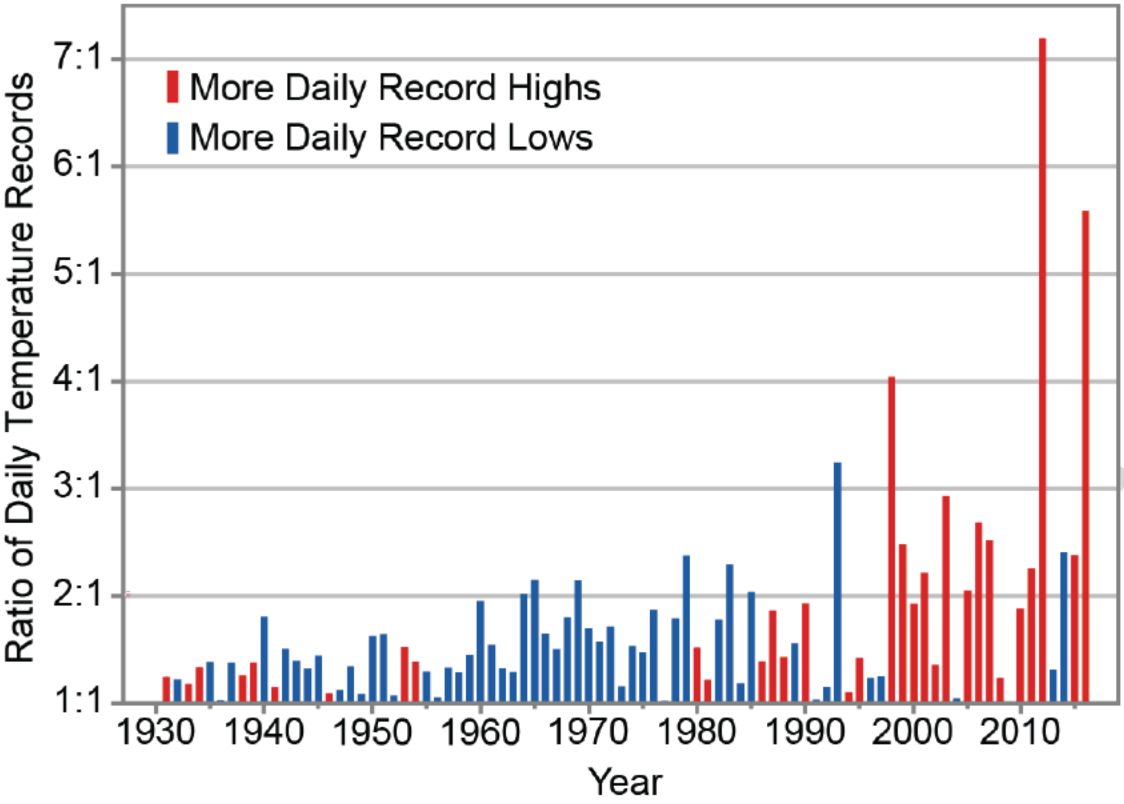


Figure ES.5: Record Warm Daily Temperatures Are Occurring More Often. Observed changes in the occurrence of record-setting daily temperatures in the contiguous United States. Red bars indicate a year with more daily record highs than daily record lows, while blue bars indicate a year with more record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

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

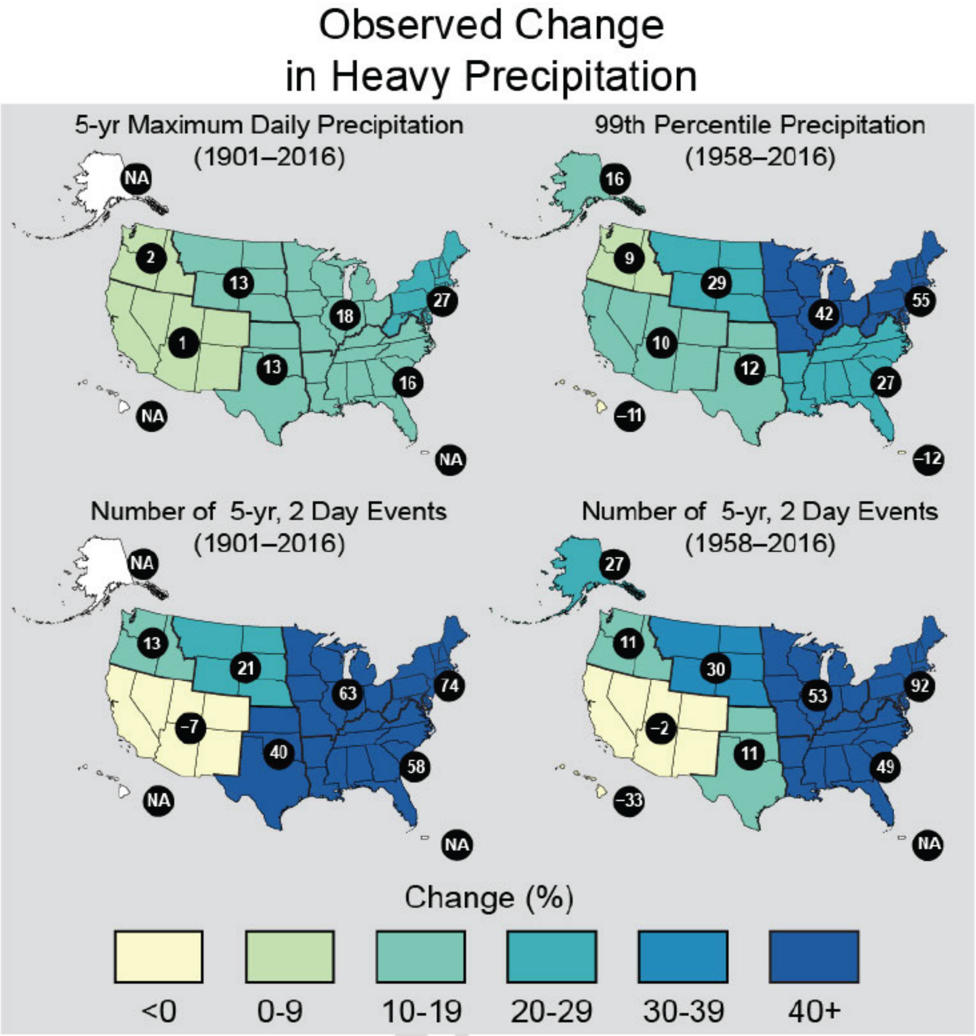


Figure ES.6: Extreme Precipitation Has Increased Across Much of the United States
These maps show the percentage change in several metrics of extreme precipitation by NCA4 region, including (upper left) the maximum daily precipitation in consecutive 5-year periods; (upper right) the amount of precipitation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

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

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

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

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

Projected Changes in Extremes

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

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

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

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

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

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

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

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

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

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

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

- Both physics and numerical modeling simulations (in general) indicate an increase in tropical cyclone intensity in a warmer world, and the models generally show an increase in the number of very intense tropical cyclones. For Atlantic and eastern North Pacific hurricanes and western North Pacific typhoons, increases are projected in precipitation rates (*high confidence*) and intensity *(medium confidence)*. The frequency of the most intense of these storms is projected to increase in the Atlantic and western North Pacific (*low confidence*) and in the eastern North Pacific (*medium confidence*). (Ch.9)

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

The Connected Climate System: Distant Changes Affect the United States

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

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

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

Changes in the Tropics can also impact the rest of the globe, including the United States. There is growing evidence that the Tropics have expanded poleward by about 70 to 200 miles in each hemisphere over the period 1979–2009, with an accompanying shift of the subtropical dry zones, midlatitude jets, and storm tracks (*medium to high confidence*). Human activities have played a role in the change (*medium confidence*), although confidence is presently low regarding the magnitude of the human contribution relative to natural variability (Ch.5).

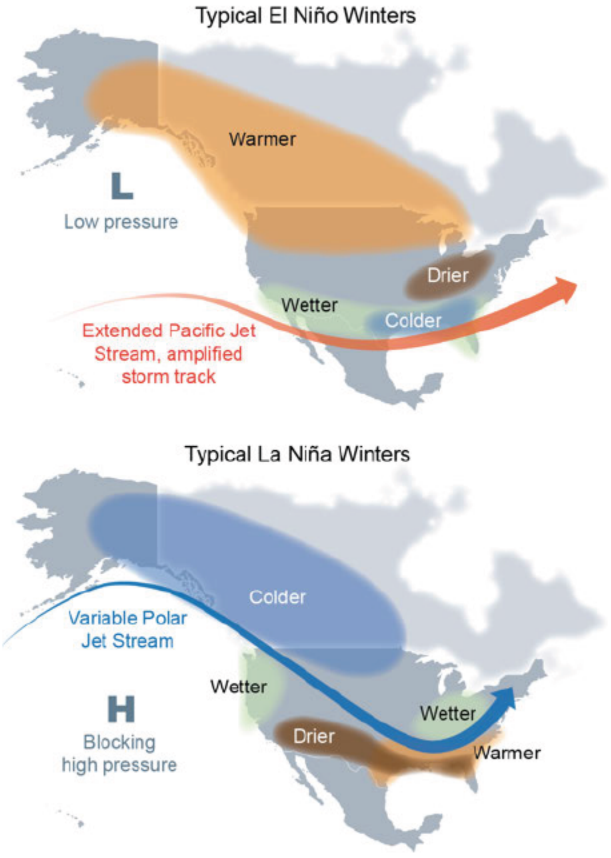


Figure ES.7. Large-Scale Patterns of Natural Variability Affect U.S. Climate
For example, this figure illustrates the typical January–March weather anomalies and atmospheric circulation during moderate to strong (top) El Niño and (bottom) La Niña. These influences over the United States often occur most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

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

Oceans Are Rising, Warming, and Becoming More Acidic

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

Global Ocean heat

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

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

Global and Regional Sea Level Rise

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

- Human-caused climate change has made a substantial contribution to GMSL rise since 1900 *(high confidence)*, contributing to a rate of rise that is greater than during any preceding century in at least 2,800 years *(medium confidence)*. (Ch.12; Fig ES.8)
- Relative to the year 2000, GMSL is *very likely* to rise by 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1–4 feet (30–130 cm) by 2100 *(very high confidence* in lower bounds*; medium confidence* in upper bounds for 2030 and 2050*; low* confidence in upper bounds for 2100*)*. Future emissions pathways have little effect on projected GMSL rise in the first half of the century, but significantly affect projections for the second half of the century *(high confidence)*. (Ch.12)

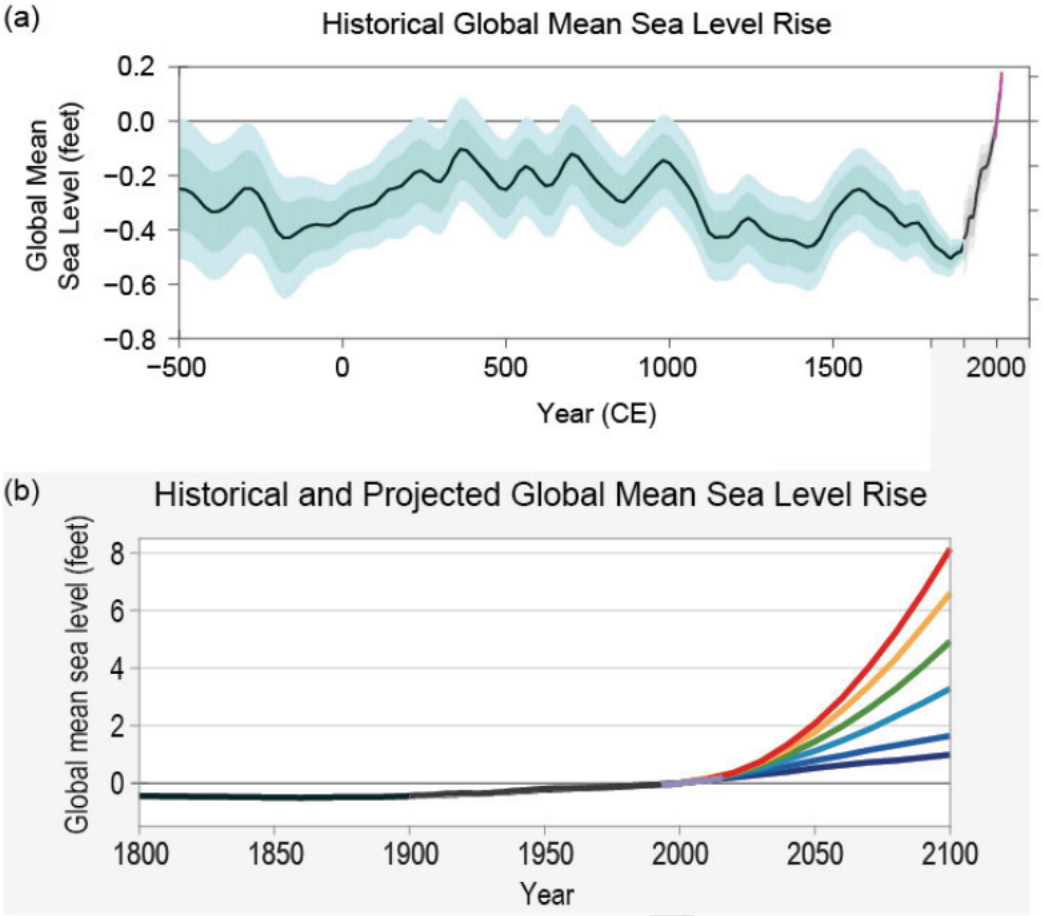


Figure ES.8 Recent Sea Level Rise Fastest for Over 2,000 Years

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

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

- Relative sea level rise in this century will vary along U.S. coastlines due, in part, to changes in Earth's gravitational field and rotation from melting of land ice, changes in ocean circulation, and vertical land motion (*very high confidence*). For almost all future GMSL rise scenarios, relative sea level rise is *likely* to be greater than the global average in the U.S. Northeast and the western Gulf of Mexico. In intermediate and low GMSL rise scenarios, relative sea level rise is *likely* to be less than the global average in much of the Pacific Northwest and Alaska. For high GMSL rise scenarios, relative sea level rise is *likely* to be higher than the global average along all U.S. coastlines outside Alaska. Almost all U.S. coastlines experience more than global mean sea level rise in response to Antarctic ice loss, and thus would be particularly affected under extreme GMSL rise scenarios involving substantial Antarctic mass loss *(high confidence)*. (Ch.12)

Coastal Flooding

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

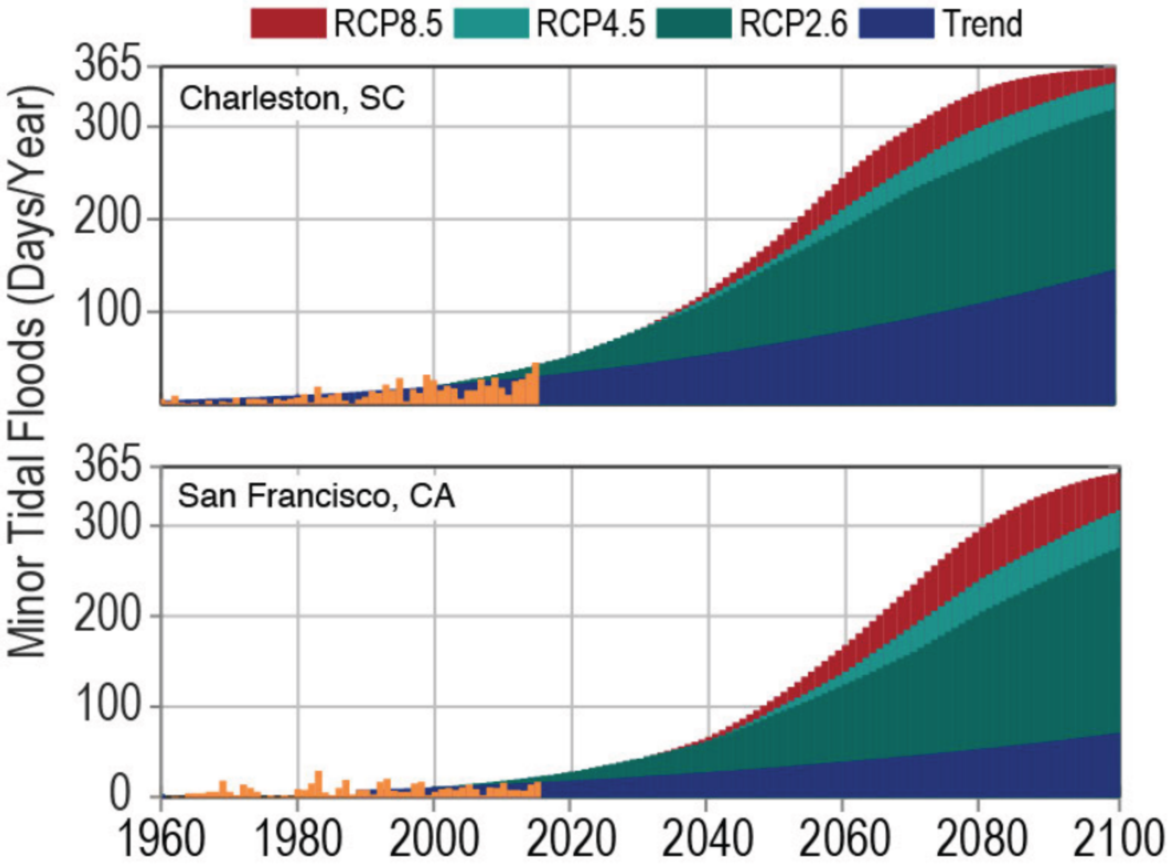


Figure ES. 9 "Nuisance Flooding" Increases Across the United States
Annual occurrences of tidal floods (days per year), also called sunny-day or nuisance flooding, have increased for some U.S. coastal cities. Historical exceedances (orange bars) for two of the locations—Charleston, SC and San Francisco,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

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

Global Ocean Circulation

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

Global and Regional Ocean Acidification

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

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

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

Ocean Oxygen

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

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

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

Arctic Temperature Increases

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

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

- Atmospheric circulation patterns connect the climates of the Arctic and the contiguous United States. Evidenced by recent record warm temperatures in the Arctic and emerging science, the midlatitude circulation has influenced observed arctic temperatures and sea ice (*high confidence*). However, confidence is low regarding whether or by what mechanisms observed arctic warming may have influenced the midlatitude circulation and weather patterns over the continental United States. The influence of arctic changes on U.S. weather over the coming decades remains an open question with the potential for significant impact. (Ch.11)

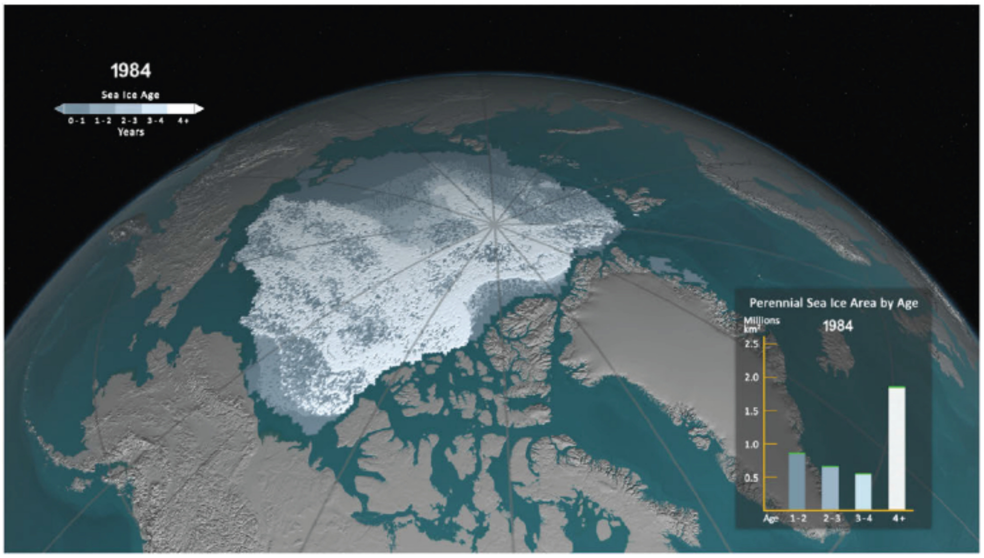
Arctic Land Ice Loss

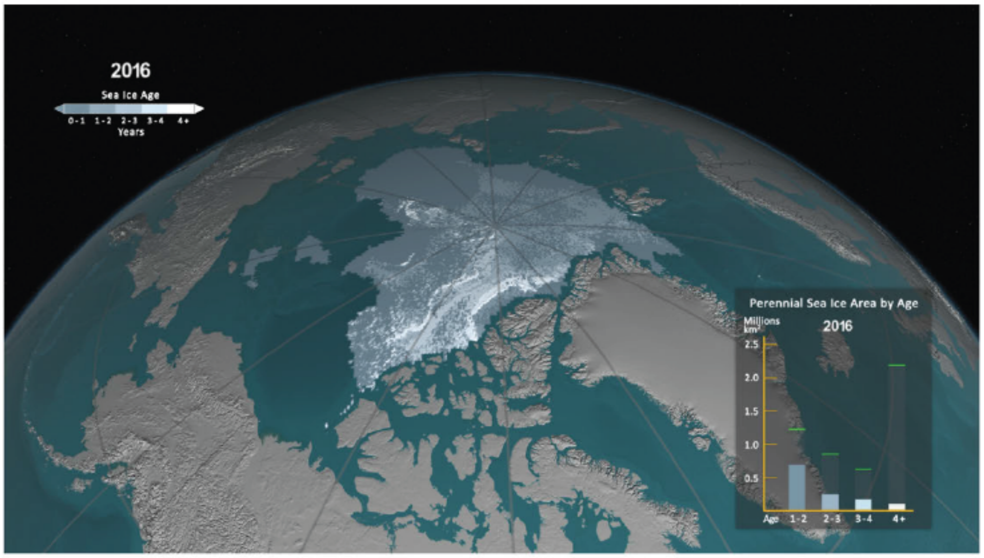
- Arctic land ice loss observed in the last three decades continues, in some cases accelerating (*very high confidence*). It is *virtually certain* that Alaska glaciers have lost mass over the last 50 years, with each year since 1984 showing an annual average ice mass less than the previous year. Over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

Arctic Sea Ice Loss

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

- Arctic sea ice loss is expected to continue through the 21st century, *very likely* resulting in nearly sea ice-free late summers by the 2040s (*very high confidence*). (Ch.11)
- It is *virtually certain* that human activities have contributed to Arctic surface temperature warming, sea ice loss since 1979, glacier mass loss, and northern hemisphere snow extent decline observed across the Arctic (*very high confidence*). Human activities have *likely* contributed to more than half of the observed September sea ice decline since 1979 (*high confidence*). (Ch.11)


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


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

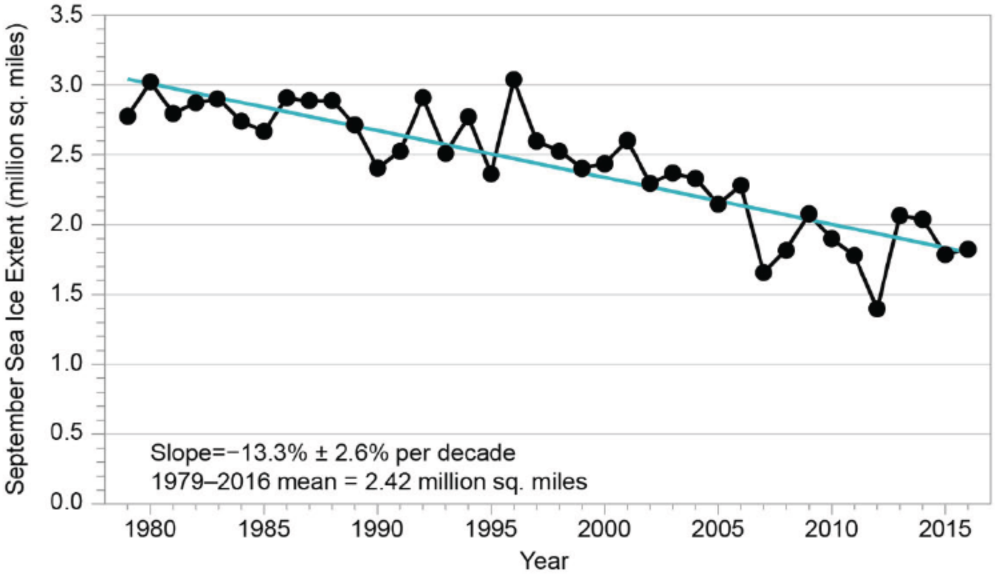

September Sea Ice Extent (million sq. miles)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Slope=−13.3% ± 2.6% per decade
1979–2016 mean = 2.42 million sq. miles
1980
1985
1990
1995
2000
2005
2010
2015
Year

Figure ES.10 Multiyear Sea Ice Has Declined Dramatically

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

From Figure 11.1 in Chapter 11.

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

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

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

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

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

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

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

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

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

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

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

There is a Significant Possibility for Unanticipated Changes

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

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

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

- Positive feedbacks (self-reinforcing cycles) within the climate system have the potential to accelerate human-induced climate change and even shift the Earth’s climate system, in part or in whole, into new states that are very different from those experienced in the recent past (for example, ones with greatly diminished ice sheets or different large-scale patterns of atmosphere or ocean circulation). Some feedbacks and potential state shifts can be modeled and quantified; others can be modeled or identified but not quantified; and some are probably still unknown. (*Very high confidence* in the potential for state shifts and in the incompleteness of knowledge about feedbacks and potential state shifts). (Ch.15)

- The physical and socioeconomic impacts of compound extreme events (such as simultaneous heat and drought, wildfires associated with hot and dry conditions, or flooding associated with high precipitation on top of snow or waterlogged ground) can be greater than the sum of the parts *(very high confidence)*. Few analyses consider the spatial or temporal correlation between extreme events. (Ch.15)
- While climate models incorporate important climate processes that can be well quantified, they do not include all of the processes that can contribute to feedbacks (Ch. 2), compound extreme events, and abrupt and/or irreversible changes. For this reason, future changes outside the range projected by climate models cannot be ruled out (*very high confidence*). Moreover, the systematic tendency of climate models to underestimate temperature change during warm paleoclimates suggests that climate models are more likely to underestimate than to overestimate the amount of long-term future change (*medium confidence*). (Ch.15)

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

A Summary of Advances Since NCA3

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

- *Detection and attribution*: Significant advances have been made in the attribution of the human influence for individual climate and weather extreme events since NCA3. (Chapters 3,6,7,8).
- *Atmospheric circulation and extreme events*: The extent to which atmospheric circulation in the midlatitudes is changing or is projected to change, possibly in ways not captured by current climate models, is a new important area of research. (Chapters 5,6,7).
- *Increased understanding of specific types of extreme events*: How climate change may affect specific types of extreme events in the United States is another key area where scientific understanding has advanced. (Chapter 9).
- *High-resolution global climate model simulations*: As computing resources have grown, multidecadal simulations of global climate models are now being conducted at horizontal resolutions on the order of 15 miles (25 km) that provide more realistic

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

- *Oceans and coastal waters*: Concern over ocean acidification, warming, and oxygen loss is increasing as scientific understanding of the severity of their impacts grows. Both oxygen loss and acidification may be magnified in some U.S. coastal waters relative to the global average, raising the risk of serious ecological and economic consequences. (Chapters 2, 13).
- *Local sea level change projections*: For the first time in the NCA process, sea level rise projections incorporate geographic variation based on factors such as local land subsidence, ocean currents, and changes in Earth's gravitational field. (Chapter 12).
- *Accelerated ice-sheet loss and irreversibility*: New observations from many different sources confirm that ice-sheet loss is accelerating. Combining observations with simultaneous advances in the physical understanding of ice sheets, leads to the conclusion that up to 8.5 feet of global sea level rise is possible by 2100 under a high emissions scenario (RCP8.5), up from 6.6 feet in NCA3. (Chapter 12).
- *Slower regrowth in Arctic sea ice area extent in fall and winter 2016–2017*: The annual Arctic sea ice extent minimum for 2016 relative to the long-term record was the second lowest on record; since 1981, the sea ice minimum has decreased by 13.3% per decade, more than 46% over the 35 years. In fall and winter 2016–2017, record-setting slow seasonal ice regrowth was the lowest since observations began in 1981. (Chapter 11).
- *Potential surprises*: Both large-scale state shifts in the climate system (sometimes called "tipping points") and compound extremes have the potential to generate unanticipated climate surprises. The further the Earth system departs from historical climate forcings, and the more the climate changes, the greater the potential for these surprises. (Chapter 15).
- *The Paris Agreement*: The Paris Agreement, which entered into force in 2016, provides a new framework for its parties for the mitigation of and adaption to climate change. This report discusses some important aspects of climate science that are relevant to the Agreement. (Chapters 4, 14).

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