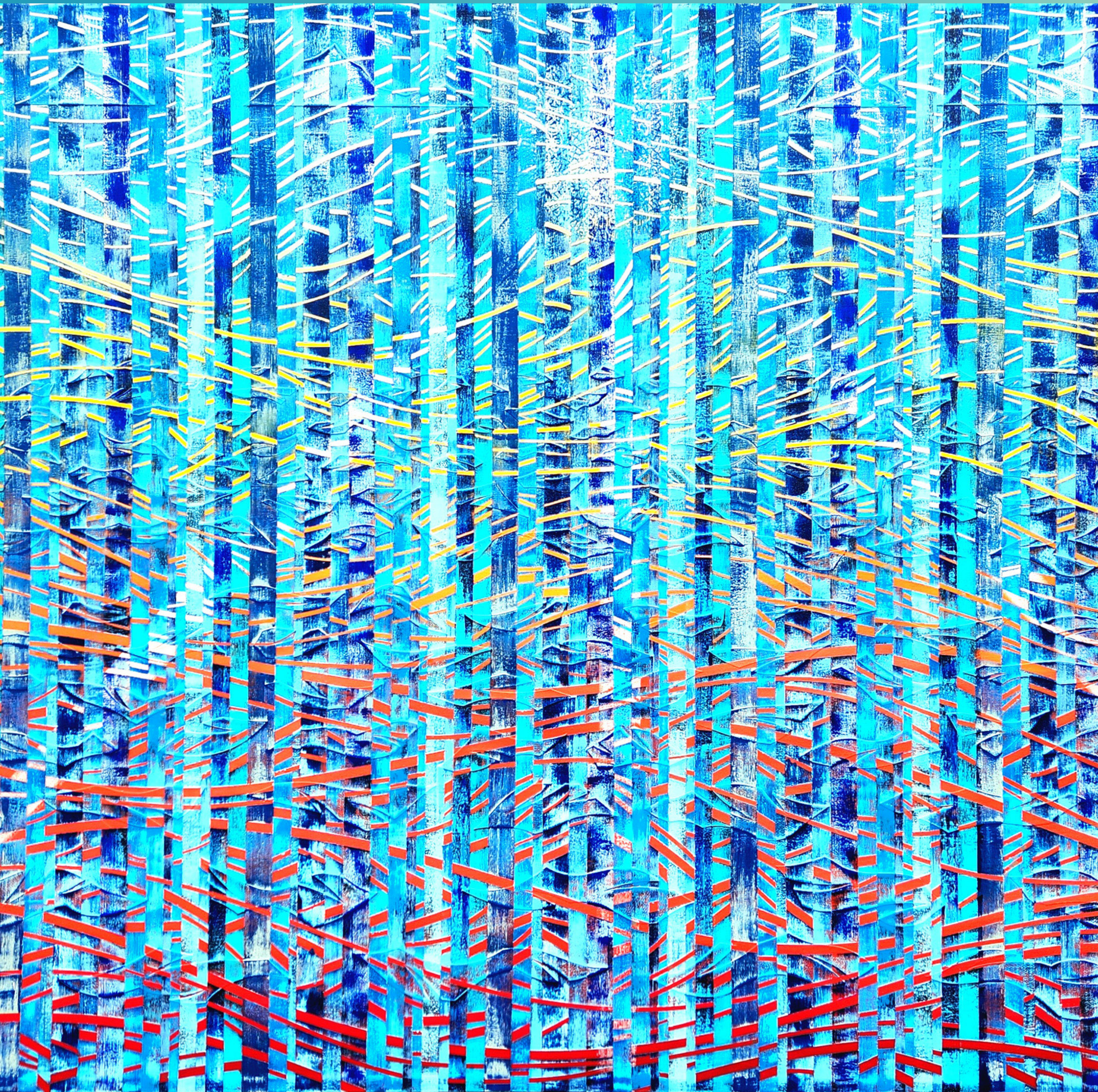
Fifth National Climate Assessment: Chapter 2

Climate Trends



Chapter 2. Climate Trends

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Introduction

Human activities are changing the climate. The evidence for warming across multiple aspects of the Earth system is incontrovertible, and the science is unequivocal that increases in atmospheric greenhouse gases are driving many observed trends and changes (KM 3.1). There are more greenhouse gases in the atmosphere primarily because humans have burned and continue to burn fossil fuels for transportation and energy generation.[1] Industrial processes, deforestation, and agricultural practices also increase greenhouse gases in the atmosphere.[1] As a result of increases in the atmospheric concentrations of these heat-trapping gases, the planet is on average about 2°F (1.1°C) warmer than it was in the late 1800s.[2,3,4,5] No natural processes known to science could have caused this long-term temperature trend. The only credible explanation for the observed warming is human activities (Ch. 3).

Climate change is happening now in the United States. Including Alaska, the continental US has been warming about 60% faster than the planet as a whole since 1970. This temperature change has driven increases in the frequency and severity of some extreme events, consistent with the scientific understanding of climate change (Ch. 3). There has always been extreme weather, which occurs even in an unchanged climate due to the natural variability of the Earth system. However, recent advances in attribution science (KM 3.3) mean that the role of climate change in some extreme events can now be quantified in real time.[6,7] For example, climate change made the record-breaking Pacific Northwest heatwave of June 2021 2° to 4°F hotter,[8] and in 2017, Hurricane Harvey's rainfall was estimated to be about 15%–20% heavier than it would have been without human-caused warming.[9,10,11]

Climate change is already affecting people in the United States. Extreme heat was estimated to be responsible for more than 700 deaths per year between 2004 and 2018,[12] although some estimates put heat-related mortality closer to 1,300 deaths annually.[13,14] Disasters are now coming more frequently and causing more damage. In the 1980s, the country experienced, on average, one (inflation-adjusted) billion-dollar weather disaster every four months.[15] Now there is one, on average, every three weeks.[15]

Disaster risk in a complex society such as the United States is never determined simply by extreme weather events. It also depends strongly on exposure (who or what lies in the path of hazards) and vulnerability (their ability to cope with hazards). Climate change interacts with existing social, political, and economic structures—increases in property values as well as increased development in hazard hotspots[16] have also contributed to the increase in billion-dollar disasters—and exacerbates existing inequalities. Certain groups are more vulnerable to extreme events due to socioeconomic or demographic factors. Americans over 65 are several times more likely to die of heat-related cardiovascular disease than younger people, while Black Americans die from heat-related diseases at a rate twice that of the general population.[17] The extreme rainfall brought by Hurricane Harvey increased the flooded area in the Greater Houston area by 14%,[18] which led to 32% more homes flooded in Harris County,[19] with a disproportionate impact on low-income Hispanic neighborhoods. The spatial distribution of climate impacts partially reflects current and past policy choices: low-income neighborhoods, including those historically affected by redlining or other discriminatory policies, can be as much as 12°F hotter during heatwaves than wealthier neighborhoods in the same city[20] and are at a substantially higher risk of flooding.[21]

Climate change has other wide-ranging consequences for people's health and well-being (KM 15.1) and the land and ocean ecosystems on which we depend (Chs. 8, 10). The 2021 Pacific Northwest heatwave, which resulted in more than 1,400 heat-related fatalities, also led to widespread die-offs of shellfish and other marine organisms (Box 10.1), tree and crop damage, and other impacts on the region's ecosystems.[15,22] Western wildfires, made more severe by climate change (Focus on Western Wildfires), have destroyed towns and infrastructure and contributed to an increase in the frequency and persistence of high levels of air pollution across the US West (Chs.14, 15).[23] These extreme events occur against a changing backdrop as climate change pushes aspects of the Earth system into a "new normal."

Long-term warming trends are associated with shifts in other aspects of the climate system. For example, both drought in the western US[24] and heavier precipitation and increased flood risk across much of the US[25] are linked to rising temperatures (KM 3.5). Sea level rise threatens the coasts (Ch. 9; Figure A4.10) and makes storm surges higher. Scientists cannot rule out the possibility of still more dramatic shifts if certain tipping elements trigger rapid and irreversible changes. While immediate and aggressive reductions in greenhouse gas emissions can mitigate future warming (KM 32.2) and reduce the risk of exceeding tipping points, temperatures will continue to increase until emissions of carbon dioxide reach net zero. When or if warming stops, long-term responses to the temperature changes that have already occurred will continue to drive changes for decades. Put simply, communities across the country are built for a climate that no longer exists.

Key Message 2.1

Climate Is Changing, and Scientists Understand Why

It is unequivocal that human activities have increased atmospheric levels of carbon dioxide and other greenhouse gases. It is also unequivocal that global average temperature has risen in response. Observed warming over the continental United States and Alaska is higher than the global average (*virtually certain*, *very high confidence*). Long-term changes have been observed in many other aspects of the climate system (*very high confidence*). The Earth system is complex and interconnected, which means changes in faraway regions are *virtually certain* to affect the United States (*very high confidence*).

Humans are increasing atmospheric concentrations of planet-warming gases, including the three main greenhouse gases produced by human activities: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O; Table 2.1; Figure A4.3). Since 1850, carbon dioxide concentrations have increased by more than 47%, nitrous oxide by 23%, and methane by more than 156%.[1] Methane is a more potent greenhouse gas than CO_2 but is shorter-lived and present in lower concentrations than CO_2. Nitrous oxide is both long-lived and more potent, but its concentrations are also lower than CO_2. Strong reductions in emissions of both CO_2 and non-CO_2 greenhouse gases are required to limit human-induced global warming to specific levels.[26]

Table 2.1. Concentrations of Greenhouse Gases That Cause Global Warming Are Increasing

Human activities have increased atmospheric concentrations of the three main greenhouse gases: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Shown below are the concentrations in 1850 and 2020 for all three gases, along with information on the atmospheric lifetimes, sources, and sinks (processes by which the gas is removed from the atmosphere).

Greenhouse Gas	1850 Concentration	2020 Concentration	Lifetime	Sources	Sinks
Carbon dioxide (CO_2)	280 parts per million (ppm)[27]	412 ppm[28]	See below*	Human activities: fossil fuel use, industrial processes, and changes in land use such as deforestation, land clearing for agriculture, and soil degradation. Natural sources: oceans, animal and plant respiration, decomposition, forest fires, volcanic eruptions.	Uptake by the biosphere on land and ocean and formation of calcium carbonate and carbonate ion leading to ocean acidification and land-based weathering
Methane (CH_4)	700 parts per billion (ppb)[29]	1,878 ppb[30]	9.1 ± 0.09 years	Human activities: agriculture, waste management, energy use, and biomass burning. Natural sources: geological, oceanic hydrates, permafrost, termites, wild animals.	Chemical reactions in the atmosphere and soil uptake
Nitrous oxide (N_2O)	270 ppb[1]	333 ppb[31]	116 ± 9 years[32]	Human activities: agriculture, fossil fuel combustion, biomass/ biofuel burning, and wastewater; atmospheric nitrogen deposition on ocean and land. Natural sources: rivers, estuaries and coastal zones, open oceans, soils under natural vegetation, atmospheric chemistry.	Stratospheric destruction via photolysis or broken down by chemical reactions

* Carbon dioxide's lifetime cannot be represented with a single value since CO_2 moves among different reservoirs within the ocean–atmosphere–land system (see "Carbon Cycle," App. 5). The rate at which this transfer of CO_2 happens between reservoirs can vary from months to thousands of years, thus making it unrealistic to provide a single numerical value for the lifetime of CO_2, unlike CH_4 and N_2O, which have specific chemical loss mechanisms in the atmosphere. Also see https://www.epa.gov/climate-indicators/greenhouse-gases.

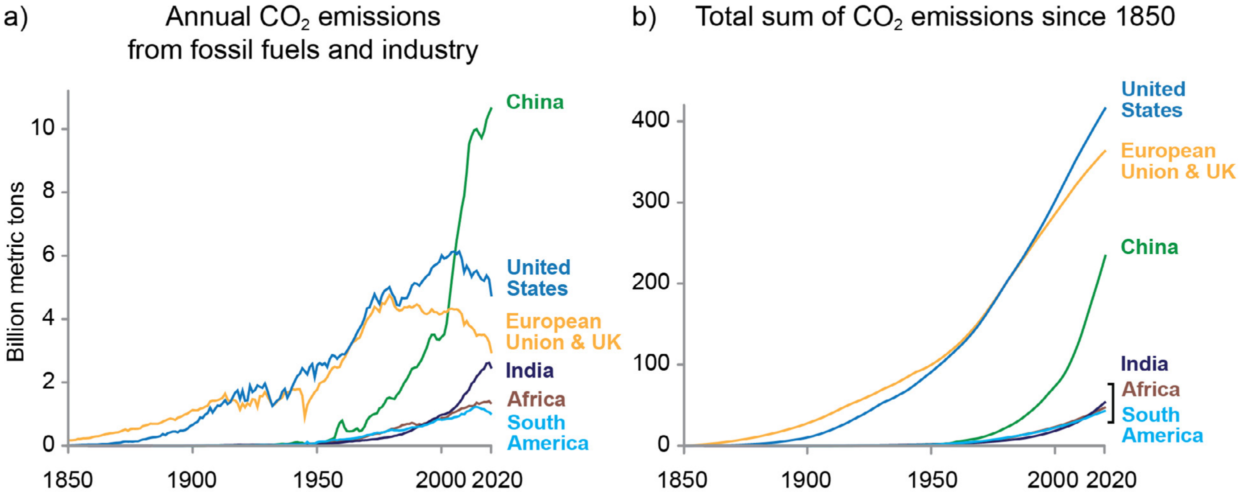
CO_2 Emitted Long Ago Continues to Contribute to Climate Change Today

The carbon dioxide not removed from the atmosphere by natural sinks lingers for thousands of years. This means CO_2 emitted long ago continues to contribute to climate change today. The long lifetime of atmospheric CO_2 is one of the primary reasons why the COVID-19 pandemic–related reduction in greenhouse gas emissions—a decrease of 7% between 2019 and 2020[33,34,35]—had no measurable impact on atmospheric CO_2 concentrations and little effect on global temperatures (Focus on COVID-19 and Climate Change).[36,37] Because of historical trends, cumulative CO_2 emissions from fossil fuels and industry in the US are higher than from any other country (Figure 2.1b).

Carbon dioxide, along with other greenhouse gases like methane and nitrous oxide, is well-mixed in the atmosphere. This means these gases warm the planet regardless of where they were emitted, and all countries that emit them contribute to the warming of the entire globe. For the first half of the 20th century, the vast majority of greenhouse gas emissions came from the United States and Europe, but emissions from the rest of the world, particularly Asia, have been rising rapidly (Figure 2.1a). In 2021, for example, US emissions were 17% lower than 2005 levels and falling. Currently, the country that emits the most CO_2 on an annual basis is China.

In order to understand the total contributions of past actions to observed climate change, additional warming from CO_2 emissions from land use, land-use change, and forestry, as well as emissions of nitrous oxide and the shorter-lived greenhouse gas methane, should also be taken into account alongside cumulative fossil CO_2 emissions. Accounting for all these factors and emissions from 1850–2021, US emissions are estimated to comprise approximately 17% of current global warming, China 12%, European Union 10%, and emissions from the 47 least-developed countries collectively 6%.[38] The present is shaped by the past; future global warming depends on decisions made today (KM 2.3).

Greenhouse Gas Emissions from the US and Other Sources



China is now the largest single-country emitter of carbon dioxide on an annual basis. The United States and Europe have emitted the majority of cumulative carbon dioxide.

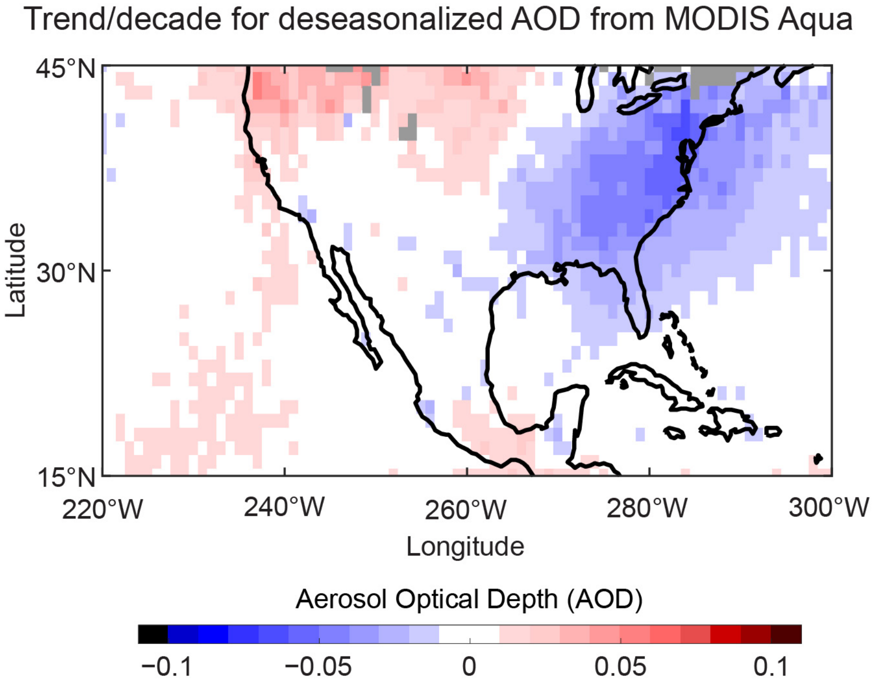
Figure 2.1. Panel (**a**) shows the annual total carbon dioxide (CO_2) emissions from fossil fuels and industry for selected world regions. China is currently the world's largest emitter of CO_2. Emissions from the US and the European Union and UK are large and falling; India, Africa, and South America emit less CO_2 on an annual basis. Panel (**b**) shows the cumulative CO_2 emissions of the same world regions. Some CO_2 emitted decades ago remains in the atmosphere today, causing the climate changes now being experienced. Figure credit: Project Drawdown.

Greenhouse Gases Are Not the Only Air Pollutants That Affect the Climate

Many of the human activities that produce greenhouse gases also produce small airborne particles known as aerosols. Aerosol emissions are an important constituent of air pollution, which is responsible for more excess deaths in the United States than murders and car accidents combined.[39] Aerosols also have climate impacts: they can scatter or absorb sunlight, which have cooling and warming effects, respectively.

Aerosols also affect climate through their effects on clouds (Ch. 3). Increased global aerosol emissions have primarily cooled the planet, partially counteracting the warming caused by greenhouse gases, but compared to CO_2 aerosols are more localized and shorter lived. Aerosol emissions in the US have dramatically decreased since the passage of the Clean Air Act and subsequent pollution control legislation (Figure 2.2), global aerosol emissions have fallen, and the location of peak aerosol emissions has shifted from North America and Europe to South and East Asia. COVID-19–related shutdowns (see Focus on COVID-19 and Climate Change) led to decreases in aerosol emissions, reducing their cooling effect. This led to a small and temporary global warming estimated at 0.05°F.[40] Long-term reductions in aerosol emissions would further reduce the cooling effect of aerosols,[41,42] which means that even stronger reductions in greenhouse gases would be required to limit warming to specific levels.

Observed Trends in Aerosol Optical Depth from 2002 to 2021



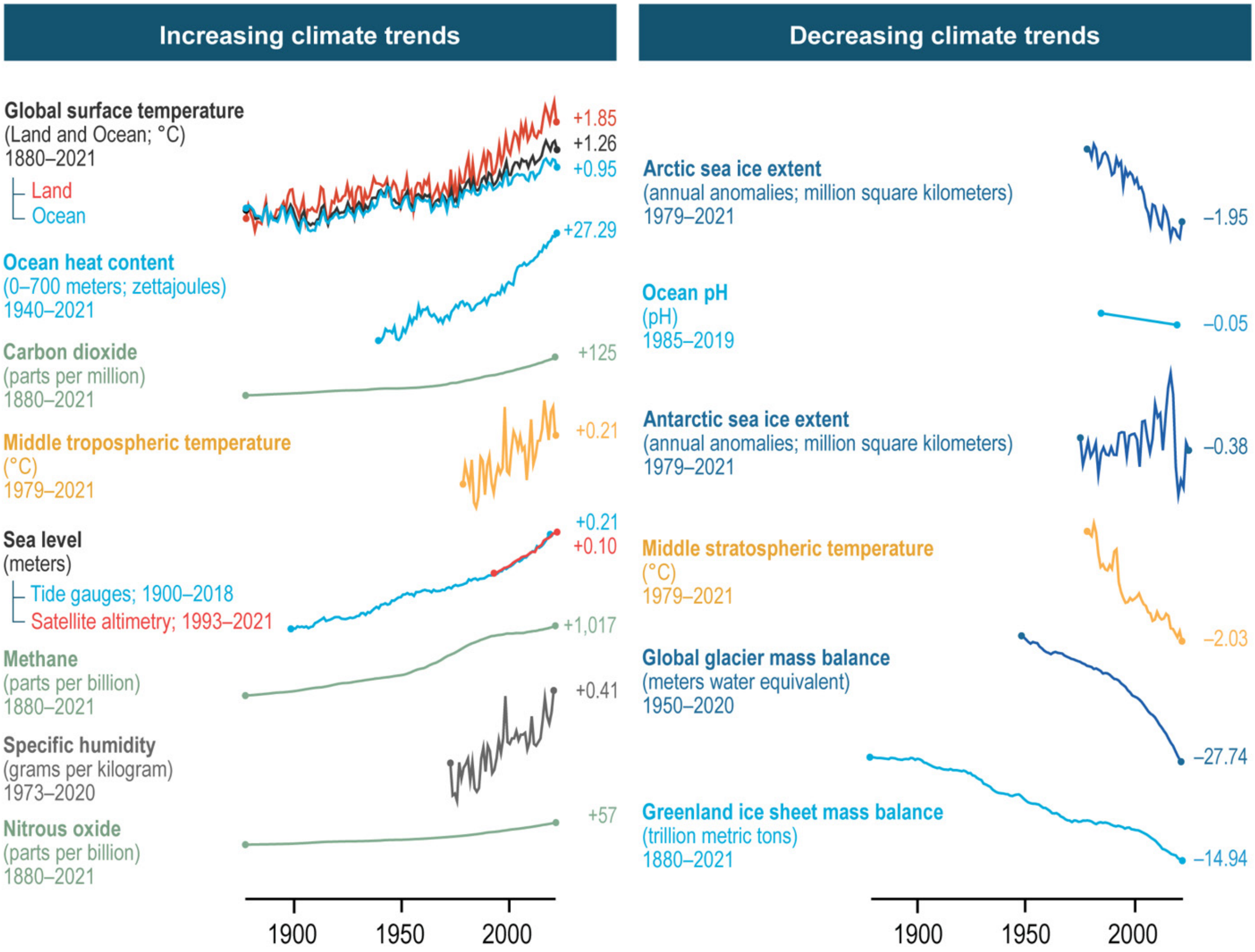
Trends in aerosol optical depth show decreases in aerosol pollution across the eastern United States.

Figure 2.2. Aerosol pollution over and downwind of the eastern US has decreased significantly in recent decades, resulting in both improved air quality and reduced cooling effects. Aerosols are tiny particles in the air that are associated with respiratory disease. Reduction of these particles means less impact on human health. These particles also reflect sunlight back to space, thus cooling the Earth's atmosphere. Reduction of these particles means less sunlight is reflected resulting in reduced cooling effects. This figure shows the trend from July 2002 to December 2021 in aerosol optical depth (AOD), a unitless measure of the total amount of aerosols in the atmosphere, as derived from satellite observations. The trend is calculated from deseasonalized AOD anomaly and is shown as change per decade. The trend over and downwind of the eastern US is significant at the 95% confidence level. Figure credit: NASA Langley Research Center.

Climate Change Is Already Here

Global average temperatures over the past decade (2012–2021) were close to 2°F (1.1°C) warmer than the preindustrial period (1850–1899).[2,3,4,5] This warming has been accompanied by several large-scale changes: loss of glaciers, ice sheet mass, and sea ice; ocean warming, acidification, and deoxygenation; increases in ocean heat content and marine heatwaves; increases in atmospheric humidity; shifting rainfall patterns and more frequent heavy precipitation; seasonal shifts including shorter winters and earlier spring and summer seasons; and changes in the biosphere (such as land and ocean species shifting poleward). Global average sea levels over the past decade were also higher than in the preindustrial period by between 7 and 9.5 inches, with more than half of this rise occurring since 1980.[43,44,45] A subset of notable global climate trends is shown in Figure 2.3.

Evidence for Climate Change Across Multiple Variables



Changes across the Earth system reflect the influence of human activities on the climate.

Figure 2.3. Climate change is apparent in many different aspects of the Earth system between 1880 and 2021. Many of these changes are evidence for a human fingerprint on the climate, reflecting the current scientific understanding of how the planet responds to external influences (Ch. 3). Global changes between the start and end of each time series are shown as numerical values to the right of each chart and are calculated by fitting each time series with a localized linear regression with a bandwidth of 30 years. Figure credit: Stripe Inc., NOAA NCEI, and CISESS NC.

The Changes We Face Are Unprecedented in Human History

Bubbles of ancient air trapped in ice cores can be used to reconstruct atmospheric concentrations of greenhouse gases over the last 800,000 years. These concentrations rise and fall due to natural processes, but human activities have increased greenhouse gases in the atmosphere rapidly and to levels unprecedented in the history of human life on Earth. Other paleoclimatic evidence indicates that the last time atmospheric CO_2 concentrations were as high as today was approximately 3.2 million years ago,[46,47] a time when global average sea levels were 18–63 feet higher than today.[48] Evidence from multiple proxy-based reconstructions of the past indicates that the rate of increase of global surface temperatures observed over the past several decades is unprecedented over the past 2,000 years.[49]

The Climate in the United States Is Changing

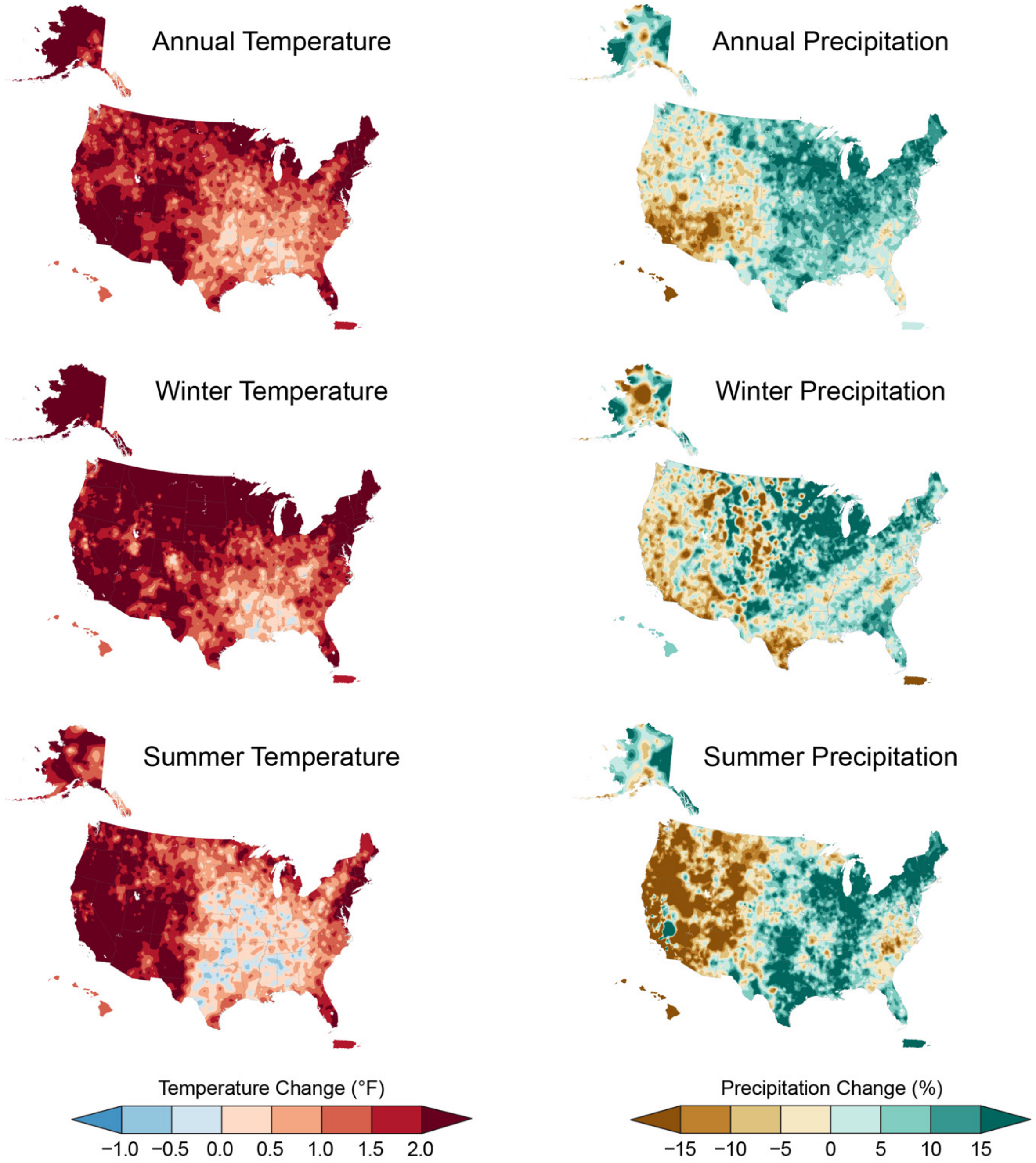
The US Is Warming Faster Than the Global Average

Temperatures in the contiguous United States (CONUS) have risen by 2.5°F and temperatures in Alaska by 4.2°F since 1970, compared to a global temperature rise of around 1.7°F over the same period. This reflects a broader global pattern in which land is warming faster than the ocean, higher latitudes are warming faster than lower latitudes, and the Arctic is warming fastest of all.[50] There are substantial seasonal and regional variations in temperature trends across the US and its territories. Winter is warming nearly twice as fast as summer in many northern states (Figure 2.4). Annual average temperatures in some areas (including parts of the Southwest, upper Midwest, Alaska, and Northeast) are more than 2°F warmer than they were in the first half of the 20th century, while parts of the Southeast have warmed less than 1°F. These regional differences are most pronounced in the summer: seasonal temperatures in some regions east of the Rockies have decreased. Studies have linked these regional trends to a combination of natural climate variability,[51,52,53,54,55] human-caused drivers such as irrigation and agricultural intensification,[56,57] and aerosol pollution (Figure 2.4; Ch. 3).[53,58] This decreasing trend has recently reversed in the southeastern US, possibly in response to decreasing aerosol amounts (Figure 2.2),[59] a shift projected to increase climate change impacts in that region (Ch. 22).

The Characteristics of Precipitation Are Changing

Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002–2021 was 5%–15% higher relative to the 1901–1960 average in the central and eastern US, a trend attributable to climate change.[60] Hawai‘i (Ch. 30) and parts of the Southwest (Ch. 28) are getting drier (Figure 2.4), recording average annual precipitation decreases between 10% and 15% over the same time period. The timing of precipitation is also changing. While the Northeast and Midwest have seen wetter conditions in all seasons, the Southeast has received more precipitation in the fall but drier conditions in spring and summer.[61] Across most of the Southwest, precipitation was more than 15% below average during summer, fall, and spring and 10%–15% above average in the winter.[62,63] The Pacific Northwest also experienced drier summers and wetter winters. More precipitation is now falling as rain rather than snow, which is contributing to reductions in snowpack and maximum annual snow equivalent (Ch. 4; Figure A4.7).

Observed Changes in Annual, Winter, and Summer Temperature and Precipitation



Temperature has increased and precipitation has changed over much of the United States.

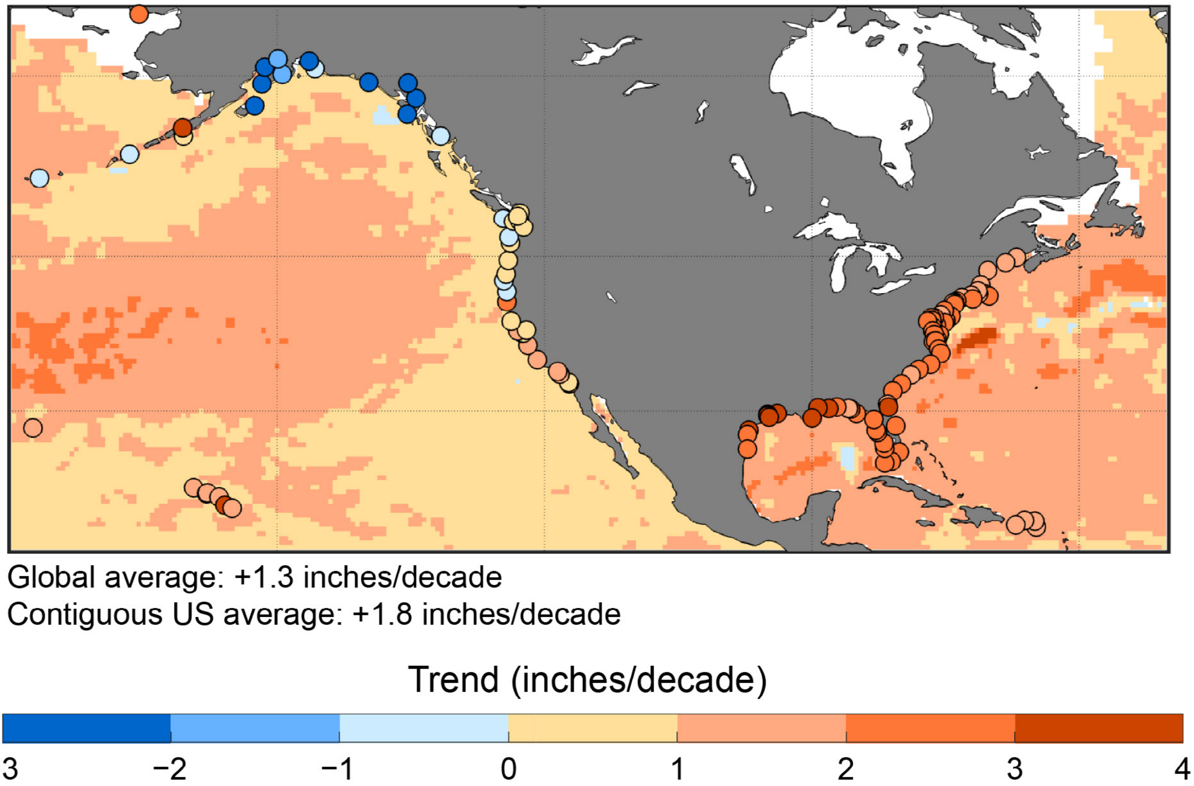
Figure 2.4. Changes shown are the difference between the annual average or seasonal temperatures (**left column**) and precipitation totals (**right column**) for the present day (2002–2021) compared to the average for the first half of the last century (1901–1960) for the contiguous United States (CONUS), Hawai‘i, and Puerto Rico; and 1925–1960 for Alaska. Temperature and precipitation estimates for CONUS and Alaska are derived from the nClimGrid dataset.[64,65] For Hawai‘i and Puerto Rico, temperature estimates are derived from NOAAGlobalTemp,[5] and precipitation estimates are derived from the Global Precipitation Climatology Center dataset.[66] Figure credit: NOAA NCEI and CISESS NC.

Sea Level Along the Continental US Coast Is Rising Faster Than the Global Average

Over the past century, average sea level along the continental US coastline has risen by about 11 inches, which is considerably more than the global average sea level rise of 7 inches.[67] In just the last three decades (1993–2020), sea level has risen at a rate of 1.8 inches per decade in the continental US compared to 1.3 inches per decade globally (Figure 2.5). Over the same period, the rate of sea level rise has accelerated both globally and in the continental US.[68] Within the US, rates of relative sea level rise (i.e., changes in sea level relative to local land surface heights, including local changes in land elevation) vary spatially, with the highest rates between 1993 and 2020 observed along the Gulf and Mid-Atlantic Coasts (greater than 2.4 inches per decade of sea level rise, as shown in Figure 2.5), the lowest rates in the Pacific Northwest (0–1 inches per decade of sea level rise, as shown in Figure 2.5), and relative sea level fall in Southeast Alaska.

Many processes have contributed to these regional differences. Land subsidence has driven very high rates of relative sea level rise along the Gulf Coast. Variations in ocean circulation and land subsidence have driven higher rates of sea level rise along the Mid-Atlantic Coast over recent decades.[69,70] On the Pacific Coast, ocean-circulation variation related to the Pacific Decadal Oscillation and local land uplift have caused lower rates of sea level rise and, in some places (such as Southeast Alaska), even sea level fall.[71] Changes in average sea level have doubled the frequency of disruptive high tide flooding in the continental United States over the past few decades.[72] In some cities, the increase in flood frequency has been even greater due to locally higher rates of sea level rise—for example, a fourfold increase in the frequency of disruptive high tide flooding events in Miami Beach, Florida, over the last 20 years.[73]

Observed Sea Level Trends



Sea levels are rising across most US coastal areas.

Figure 2.5. Satellite and tide gauge data show trends in sea level rise during 1993–2020 that are, on average, greater than global trends. Sea levels are not rising uniformly across US coastlines. The highest rates of sea level rise have occurred along the Gulf Coast and Atlantic Coast, with lower rates on the Pacific Coast and sea level fall along parts of the Alaska Coast. Rates of sea level rise in Hawai‘i and Puerto Rico are closer to the global average. Adapted from Sweet et al. 2022.[67]

Oceans Are Changing

The oceans are warming along all US coasts, but not all areas are warming at the same rate.[74,75] Surface waters along the Alaska and Northeast coastlines are warming faster than in most other regions due to climate change impacts on weather and ocean circulation in those regions (KMs 21.2, 29.5).[76] Oxygen minimum zones (areas of the deeper ocean where oxygen levels are low) have expanded in volume since 1970, particularly in Alaska waters, with negative consequences for fisheries (Ch. 10).[77,78,79] Dead zones—areas in the coastal ocean where oxygen levels seasonally drop, sometimes causing massive die-offs of marine life—are happening in more places around the country, with climate change one of many factors contributing to their expansion.[77,80] Acidification, caused by rising levels of atmospheric CO_2 being absorbed by the ocean (KM 3.4; Figure 3.9), has changed the carbonate chemistry of US offshore and coastal waters at variable rates, impacting marine life.[81] Acidification in offshore and open ocean waters tracks the global average trends,[1] but changes in US coastal waters depend on regional upwelling conditions (Ch. 27) and acidifying contributions from land and nutrient and freshwater inputs.[82,83]

Sea and Lake Ice Is Decreasing

Sea ice has dramatically retreated from Alaska coastal seas over the last several decades at rates that exceed retreat in other parts of the Arctic Ocean (Ch. 29).[79,84] In 2018, sea ice in the Bering Sea of Alaska reached a record low at less than half the average winter extent since 1979.[85] Throughout North America and the Arctic, lake ice area and seasonal duration have also notably decreased during the satellite era (Ch. 24).[86,87]

Changes Outside National Borders Affect the United States

Warming in the Tropics Affects the Entire United States

Observed changes in atmospheric circulation are shifting the distribution of precipitation throughout the tropics and subtropics, resulting in greater precipitation variability for Caribbean and Pacific islands (Chs. 3, 23, 30).[88] These shifts are also thought to extend tropical cyclone tracks farther into the midlatitudes,[89] especially in the West Pacific basin. Tropical cyclone activity in the West Pacific has also been linked to an intensifying effect on the El Niño–Southern Oscillation (ENSO).[90,91,92] ENSO itself has tended toward more extreme events since the 1950s[93] that strongly impact the US-Affiliated Pacific Islands (Ch. 30) but also heavily influence temperature and precipitation patterns in several continental US regions,[94,95,96] as well as the development of tropical cyclones in the Pacific and Atlantic basins.[97] The tropics are also a key source of moisture for atmospheric rivers and tropical storms that bring precipitation to much of the country. As the tropics warm, the subsequent increase in moisture is intensifying the precipitation associated with these systems across the western and eastern United States.[98,99]

Ice Sheet Changes in Greenland and Antarctica Contribute to US Sea Level Rise

The pattern of mass loss from glaciers and ice sheets outside the United States also has an important influence on the spatial pattern of sea level rise along US coasts, as ice losses in Antarctica lead to more sea level increase along the US Atlantic Coast than equivalent ice losses in Greenland, due to gravitational changes associated with the redistribution of mass on the Earth's surface.[100,101] Improved estimates of sea level changes during warm periods in Earth's prehistory are now directly being used to calibrate projections of the upper bound of future sea level rise.[102,103] The closest analog for current rates of sea level rise, and those that may occur in the next century, are past warm periods when the Greenland and Antarctic ice sheets were considerably smaller than their present state and global average sea level was 10 or more feet higher.[104]

Arctic Changes Affect Weather in the Midlatitudes

The Arctic is warming faster than much of the world, and Arctic sea ice is declining rapidly as a consequence.[49] There is emerging evidence from modeling studies and observations that these changes in the Arctic are affecting atmospheric circulation and extreme weather across the United States. In summer, the temperature contrast between the Arctic and the midlatitudes has decreased, weakening the midlatitude jet stream and making certain weather regimes more persistent.[105] This has led to more persistent hot and dry extremes over parts of North America.[105,106,107] However, the connection between Arctic warming and winter weather is still uncertain. In winter, the influence of natural climate variability and the lack of consistency between observations and modeling-based studies make it difficult to connect changes occurring in the Arctic and winter severe weather.[108,109] However, some recent studies suggest that Arctic warming results in increasing disruptions of the stratospheric polar vortex that cause cold air from the Arctic to spill down over the United States, as seen in recent severe winter weather events such as the February 2021 cold snap that affected large parts of the country (Figure 26.7).[110,111,112] Notably, this Arctic air, while still cold in absolute terms, is warmer than it used to be four decades ago.

Key Message 2.2

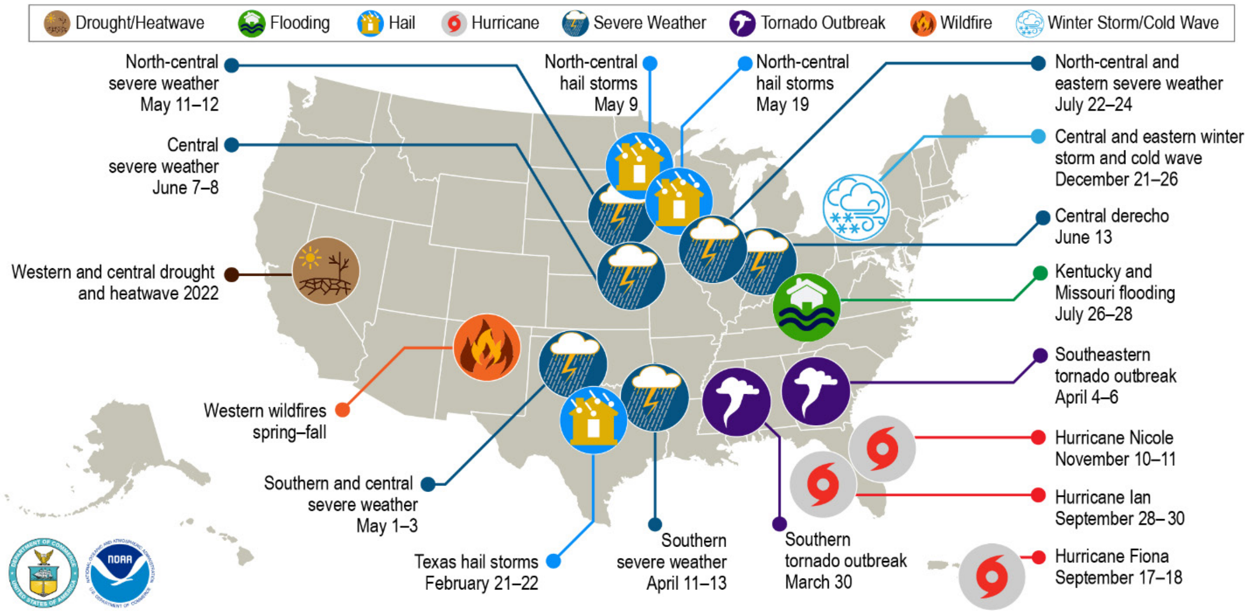
Extreme Events Are Becoming More Frequent and Severe

Observations show an increase in the severity, extent, and/or frequency of multiple types of extreme events. Heatwaves have become more common and severe in the West since the 1980s (*high confidence*). Drought risk has been increasing in the Southwest over the past century (*very high confidence*), while at the same time rainfall has become more extreme in recent decades, especially east of the Rockies (*very high confidence*). Hurricanes have been intensifying more rapidly since the 1980s (*high confidence*) and causing heavier rainfall and higher storm surges (*high confidence*). More frequent and larger wildfires have been burning in the West in the past few decades due to a combination of climate factors, societal changes, and policies (*very high confidence*).

Climate Change Is Not Just a Problem for Future Generations, It's a Problem Today

The number and cost of weather-related disasters have increased dramatically over the past four decades, in part due to the increasing frequency and severity of extreme events and in part due to increases in exposure and vulnerability. In 2022 alone, the United States experienced 18 weather and climate disasters with damages exceeding $1 billion (Figures 2.6, A4.5). There is increasing confidence that changes in some extreme events are driven by human-caused climate change (KM 3.5).

Billion-Dollar Weather and Climate Disasters in 2022



This map denotes the approximate location for each of the ***18 separate billion-dollar weather and climate disasters that impacted the United States in 2022.***

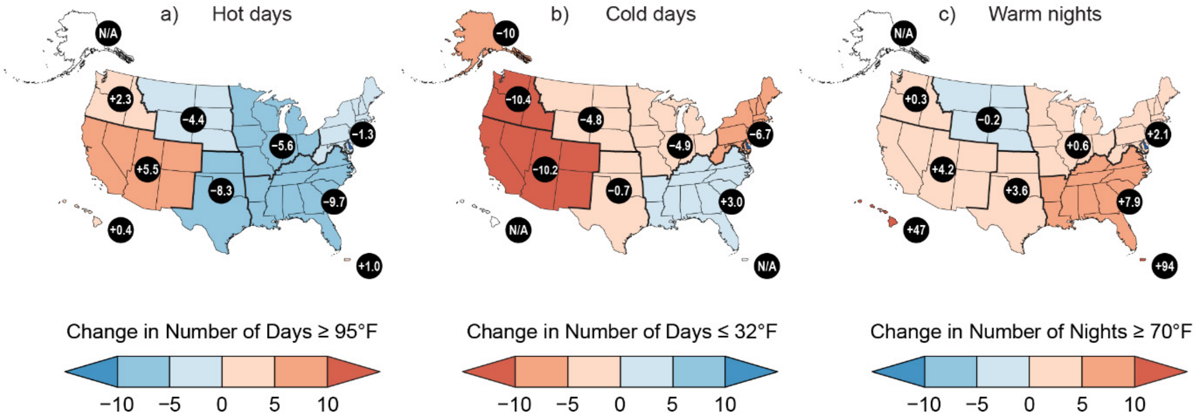
The US experienced 18 billion-dollar weather and climate disasters in 2022.

Figure 2.6. In the 1980s, there was one weather/climate disaster event with losses exceeding $1 billion approximately every four months. By the 2010s, there was one every three weeks or less. In 2022, there were 18 such events that affected the United States. These events included 1 drought event, 1 flooding event, 11 severe storm events (including tornadoes, hail storms, and straight-line winds), 3 tropical cyclone events, 1 wildfire event, and 1 winter storm event. Overall, these events resulted in the deaths of 474 people and had significant economic effects on the areas impacted. Source: NCEI 2022.[15]

The Risk of Temperature Extremes Is Changing

By some measures, the most extreme heatwaves on record in the United States occurred during the Dust Bowl era of the 1930s.[113] This serves as a historical reminder of the societal consequences of extreme heat. Globally, such heatwaves are becoming more frequent, and in recent decades the western United States has been following those trends. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021. The western US has been particularly affected by extreme heat since the 1980s (Figure 2.7), experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US.[114] By contrast, the number of very hot days has actually decreased across the central and eastern regions due to summer cooling trends in the region (Figure 2.7; Ch. 22). This does not, however, mean the central and eastern US are not affected by heat. The impacts of extreme high temperatures are more severe if such conditions persist for several days, and overall, multiday heatwaves have become hotter, more frequent, larger, and longer lasting in recent decades.[115,116,117] Across 50 large US cities, the US Global Change Research Program heatwave indicator (https://www.globalchange.gov/indicators/heat-waves) shows that the average number of heatwaves has doubled since the 1980s, and the length of the heatwave season has increased from about 40 days to about 70 days.[118] Even the ocean is experiencing extreme heat: marine heatwaves—prolonged periods of discrete (from days to several months) anomalously high sea surface temperatures—have now been documented in every US marine system (KMs 8.2, 10.1, 21.2, 27.2, 28.2, 30.4; Box 10.1; Figure 29.1).[119]

Observed Changes in Hot and Cold Extremes



Hot days have increased in the West, hot nights have increased nearly everywhere, and cold days have decreased.

Figure 2.7. Over much of the country, the risk of warm nights has increased while the risk of cold days has decreased. The risk of hot days has also increased across the western US. This figure shows the observed change in the number of (**a**) hot days (days at or above 95°F), (**b**) cold days (days at or below 32°F), and (**c**) warm nights (nights at or above 70°F) over the period 2002–2021 relative to 1901–1960 (1951–1980 for Alaska and Hawai‘i and 1956–1980 for Puerto Rico). Data were not available for the US-Affiliated Pacific Islands and the US Virgin Islands. Figure credit: Project Drawdown, Washington State University Vancouver, NOAA NCEI, and CISESS NC.

The number of cold days (on which the temperature drops below freezing) has decreased across CONUS (except in the Southeast, where the number of days below freezing is small to begin with). Despite some recent damaging cold events, overall cold extremes are becoming less frequent and milder (Figure 2.7).[120,121]

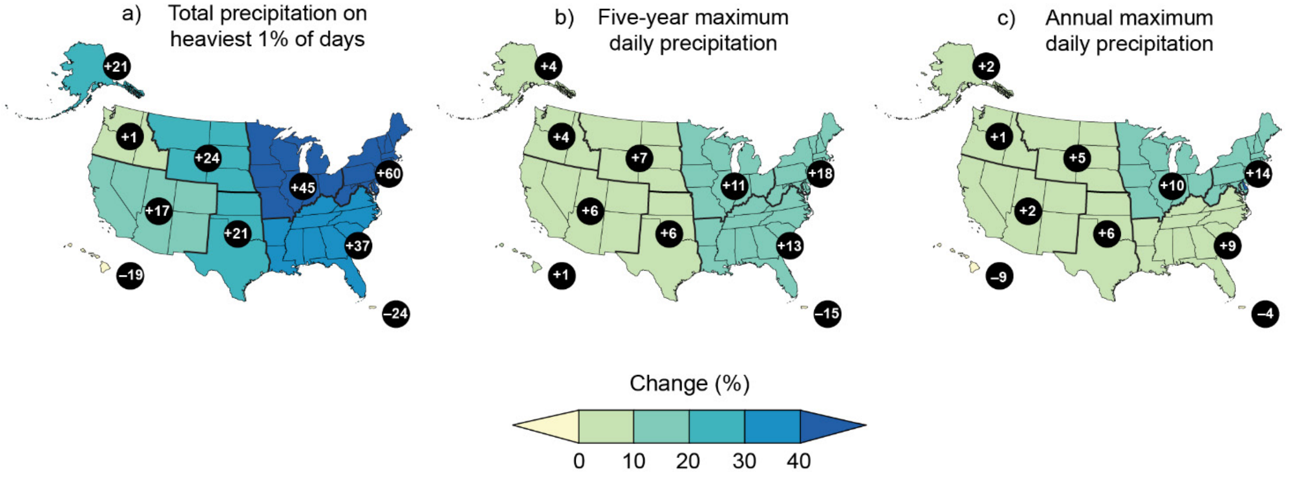
Nighttime temperatures are rising faster than daytime temperatures, and the number of nights where the temperature never falls below 70°F is increasing everywhere in the US except the Northern Great Plains (Figure 2.7). The extent of CONUS experiencing hot summer nights is growing at a faster rate than the extent experiencing hot summer days.[121,122] Temperatures are generally lower at night, allowing human (and animal) bodies, crops, and the built environment to cool down. For that reason, an increase in the frequency and intensity of warm nights can have a significant impact on human health, crop yields, and more.

Rainfall Is Becoming More Extreme

Since the 1950s, there has been an upward trend in heavy precipitation across the contiguous US (Figure 2.8).[25] This increase is driven largely by more frequent precipitation extremes, with relatively smaller changes in their intensity. The largest increase in the number of extreme precipitation days (defined as the top 1% of heaviest precipitation events) has occurred over the Northeast (an increase of around 60%) and Midwest (around 45%), along with increases of more than 10% in their annual and 5-year maximum amount (Figure 2.8). These changes have contributed to increases in river and stream flooding in these regions.[123,124] The increase in frequency and intensity of precipitation extremes is evident across a broad range of event durations (from 1 to 30 days) and return intervals (1 to 20 years), particularly east of the Rocky Mountains.[125]

There is robust evidence that human-caused warming has contributed to increases in the frequency and severity of the heaviest precipitation events across nearly 70% of the US.[126,127] Paleoclimate records derived from tree-ring growth provide evidence that summer moisture has increased over the past century in parts of New England,[128] the central-eastern US,[129] and the northern Mississippi River valley.[130]

Observed Changes in the Frequency and Severity of Heavy Precipitation Events



Heavy precipitation events are becoming more frequent and intense across much of the country.

Figure 2.8. The frequency and intensity of heavy precipitation events have increased across much of the United States, particularly the eastern part of the continental US, with implications for flood risk and infrastructure planning. Maps show observed changes in three measures of extreme precipitation: (**a**) total precipitation falling on the heaviest 1% of days, (**b**) daily maximum precipitation in a 5-year period, and (**c**) the annual heaviest daily precipitation amount over 1958–2021. Numbers in black circles depict percent changes at the regional level. Data were not available for the US-Affiliated Pacific Islands and the US Virgin Islands. Figure credits: (a) adapted from Easterling et al. 2017;[131] (b, c) NOAA NCEI and CISESS NC.

Drought Risk Is Complex and Changing

Drought is such a complex phenomenon that it is a challenge to even define what it is: more than 150 different definitions have appeared in the scientific literature.[132] Broadly, drought results when there is a mismatch between moisture supply and demand. Meteorological drought happens when there is a severe or ongoing lack of precipitation. Hydrological drought results from deficits in surface runoff and subsurface moisture supply. Drying soil moisture affects crop yields and can lead to agricultural droughts. The timing of droughts is also complex. Droughts can last for weeks or decades. They may develop slowly over months or come on rapidly. A drought may be immediately apparent or detectable only in retrospect.

Despite this complexity, some robust regional trends are emerging. Colorado River streamflow over the period 2000–2014 was 19% lower than the 20th-century average,[133] largely due to a reduction in snowfall, less reflected sunlight, and increased evaporation.[134] The period 2000–2021 in the Southwest had the driest soil moisture of any period of the same length in at least the past 1,200 years.[135] While this drought is partially linked to natural climate variability, there is evidence that climate change exacerbated it, because warmer temperatures increase atmospheric “thirst” and dry the soil.[24,136,137,138] Droughts in the region are lasting longer[139] and reflect not a temporary extreme event but a long-term aridification trend—a drier “new normal”[140] occasionally punctuated by periods of extreme wetness consistent with expected increases in precipitation volatility in a warming world.[141,142]

The Southwest is the only region in which the total area of unusually dry soil moisture is increasing.[143] In the eastern regions of the country, hydrological droughts have become less frequent since the late 19th century due to increases in precipitation that compensate for warming-driven increases in evaporation (Figures 2.4, A4.9).[144] However, there is evidence that the likelihood of drought in the Northeast did not decrease as much as would be expected given these wetter conditions[145] and that higher increases in evapotranspiration make the Southeast more drought-prone than the Northeast (Ch. 22). Additionally, much of the US is vulnerable to rapid-onset flash droughts that can materialize in a matter of days, driven by extreme high temperatures or wind speeds and a lack of rainfall.[146,147] These events are difficult to predict and prepare for, and can have outsized impacts.[148] There is evidence that these events are drying out soil more quickly as the world warms.[149]

Storms Are Changing

Changes in some types of storms are also apparent. Over the past three decades, heavy snowfalls have been more frequent over the Northeast,[111] a trend consistent with warming in the western Atlantic Ocean and increasingly frequent Arctic air outbreaks from polar vortex disruptions.[110] Atmospheric rivers along the Pacific Coast have become warmer over the past several decades[150] and have transported larger amounts of moisture into the West because of increases in Pacific Ocean temperatures.[151]

There is no long-term trend in the frequency of landfalling hurricanes in the United States since the late 19th century, but there has been an increase in basin-wide hurricane activity in the North Atlantic since the early 1970s.[152,153] In addition to recent increases in storm frequency, evidence continues to build that hurricanes are changing in other dangerous ways. Tropical cyclones have been intensifying more rapidly since the early 1980s,[154,155] leaving communities with less time to prepare. Hurricanes tend to lose energy as they move away from the ocean, but the rate of this hurricane decay has slowed since the 1960s, allowing storms to extend somewhat farther inland.[156] There has been a 17% decrease in the speed of movement of storms in the North Atlantic basin since 1900,[157] as well an increased tendency for storms along the North American coast to meander and stall since the 1950s.[158] Slower-moving storms can result in more heavy rainfall, wind damage, storm surge, and coastal flooding; notably, after accounting for changes in the value of property and other assets placed in harm's way, hurricane damage in the United States has generally increased since 1900.[159]

Changes in smaller-scale, short-lived severe weather such as tornadoes and thunderstorms are more difficult to assess, and direct observations of those events and the conditions associated with them are incomplete.[160] While the average annual number of tornadoes appears to have remained relatively constant, there is evidence that tornado outbreaks have become more frequent,[161] that tornado power has increased,[162] that tornado activity is increasing in the fall,[163] and that "Tornado Alley" has shifted eastward.[164] The complexes of thunderstorms that bring substantial precipitation to the central United States during the warm season have become more frequent and longer-lasting over the past two decades.[165]

Thunderstorms are associated with other important hazards, including hail and cloud-to-ground lightning. Direct observational records for these hazards are largely insufficient for identifying trends due to factors including observer biases, limited length of the record, and changes in the observing systems.[166,167] However, days with environmental conditions conducive to producing large hail (greater than 2 inches in diameter) have become more frequent over the central and eastern US and parts of the Pacific Northwest.[168]

A Combination of Factors Is Increasing Fire Risk

Much of the country is experiencing more intense and frequent wildfires associated with warming and drought[16,169] and aggravated by the reduction in Indigenous land-use and fire stewardship practices that have been critical for past management of fires.[170,171] Over the past 1,000 years, warm temperatures and droughts have tended to increase the area burned by wildfires in the West, including the Pacific Northwest and Rockies.[172] In the period 1979–2020, human-caused warming was responsible for nearly 68% of the observed increase in aridity in the West, creating the conditions that drove growth in the acreage burned by wildfires.[173] In the Rockies, higher temperatures, changes in precipitation, and fire stress have led to major ecological changes, including the disappearance of forests (Ch. 7).[174] Fire history records derived from tree rings and fire scars from forests in the Rocky Mountains show that for most of the past 2,000 years, cooler, wetter conditions, combined with Indigenous fire stewardship practices, limited fires.[171] However, greenhouse gas–induced warming and drying and the spread of invasive vegetation types (KM 8.2) have combined with forest management policy choices and the limitation of Indigenous sovereignty to contribute to new extreme fire regimes and more frequent fires.

Lightning and human activities are both sources of wildfire ignitions in the US. Lightning is a dominant source across much of the western US and is associated with larger and more intense fires, while humans are a dominant source across the eastern US and along the Southern California coastline.[167,175,176] Both lightning-caused and human-caused fires have increased between 1992 and 2012.[175] While rising populations, development, and a growing wildland–urban interface contribute to the increase in human-caused fires,[177] there is no clear evidence of changes in lightning activity.[178,179] Changes in lightning activity are challenging to detect due to the lack of long-term satellite measurements and uncertainties in ground-based lightning detection networks.[167]

Key Message 2.3

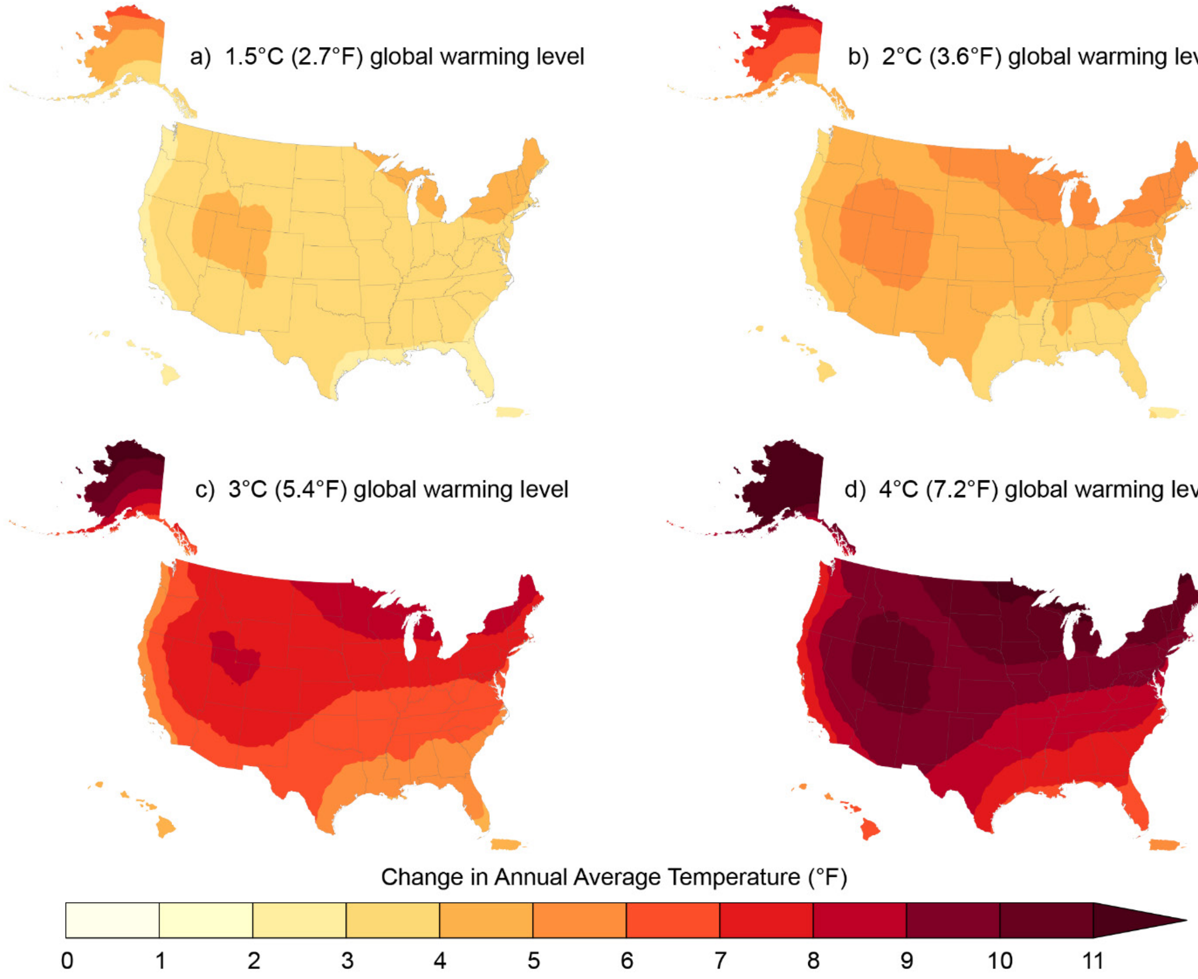
How Much the Climate Changes Depends on the Choices Made Now

The more the planet warms, the greater the impacts—and the greater the risk of unforeseen consequences (*very high confidence*). The impacts of climate change increase with warming, and warming is *virtually certain* to continue if emissions of carbon dioxide do not reach net zero (*very high confidence*). Rapidly reducing emissions would *very likely* limit future warming (*very high confidence*) and the associated increases in many risks (*high confidence*). While there are still uncertainties about how the planet will react to rapid warming and catastrophic future scenarios that cannot be ruled out, the future is largely in human hands.

As the World Warms, the United States Warms More

Every increment of global warming leads to larger increases in temperature in many regions, including much of the United States (Figure 2.9). The Paris Agreement calls for limiting global warming to "well below 2°C" relative to preindustrial temperatures, preferably to 1.5°C, and domestic and international emissions targets are generally expressed in these terms. To mirror this language, where possible, trends in this section are reported in terms of the global warming level (GWL): the global average temperature change in degrees Celsius relative to preindustrial temperatures. At a GWL of 2°C (3.6°F), the average temperature across the United States is *very likely* to increase between 4.4°F and 5.6°F (2.4°C and 3.1°C). For every additional 1°C of global warming, the average US temperature is projected to increase by around 2.5°F (1.4 °C). The northern and western parts of the country are *likely* to experience proportionally greater warming (Figure 2.9).

Projected US Temperature Changes at 1.5°C, 2°C, 3°C, and 4°C of Global Warming



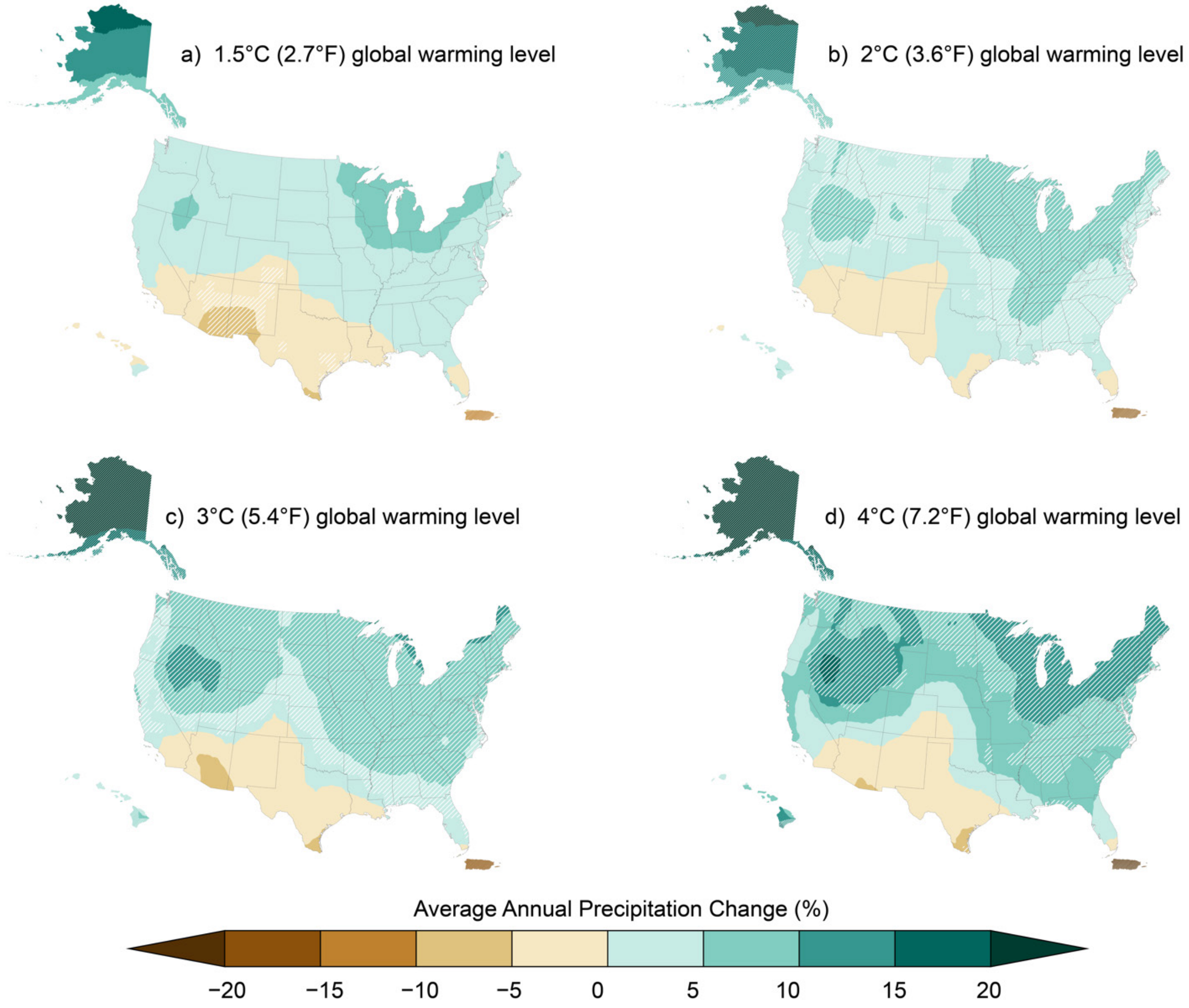
The United States is projected to warm faster than the global average.

Figure 2.9. As the world warms, the US warms more. Projected temperature rises are larger in the northern and western portions of the country and are most severe in the Arctic. These maps show projected changes in annual average temperature (°F) for various global warming levels (1.5°, 2.0°, 3.0°, and 4.0°C). Changes are relative to the period 1851–1900. Based on CMIP6. Data were not available for the US-Affiliated Pacific Islands. Figure credit: NOAA NCEI and CISESS NC.

Some Regions Will Get Wetter While Others Will Get Drier

Precipitation changes also scale with global warming, but these projections vary by location (Figure 2.10) and are less certain than temperature changes. As global temperatures increase, annual average precipitation is *very likely* to increase in the northern and eastern regions of CONUS and in Alaska, more likely than not to decrease in the Southwest and Texas, and *likely* to decrease in the Caribbean. Changes to the seasonal cycle of precipitation are also expected: in the Northwest, precipitation increases are *very likely* to occur during the winter wet season and decrease in the summer. In a warmer world, it is *virtually certain* that less precipitation will fall as snow, leading to large reductions in mountain snowpack and decreases in spring runoff in the mountain West (Chs. 4, 27, 28; Figure A4.7).

Projected US Precipitation Changes at 1.5°C, 2°C, 3°C, and 4°C of Global Warming



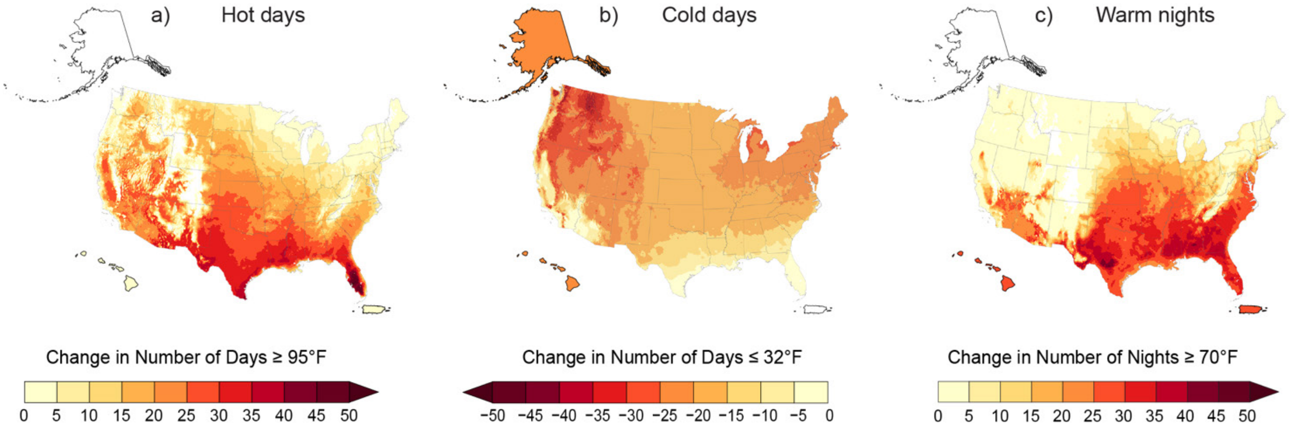
Precipitation changes are projected to be larger at higher levels of warming.

Figure 2.10. These maps show projected changes in average annual precipitation (%) for various global warming levels (1.5°, 2.0°, 3.0°, and 4.0°C). Precipitation is projected to increase with warming in the North and East and to decrease in the Southwest and the Caribbean. Changes are relative to the period 1851–1900. Based on CMIP6. Data were not available for the US Affiliated Pacific Islands. Hatching indicates areas where 80% or more of the models agree on the sign of the change. Figure credit: Project Drawdown, Stripe Inc., NOAA NCEI, and CISESS NC.

The Risk of Extreme Heat Increases with the Global Warming Level

Recent trends in extreme heat and precipitation foreshadow what is to come in a warmer world. The connection between warming and heatwaves is well understood: at the very basic level, as average temperatures warm, the risk of extreme temperatures and record-breaking temperatures goes up (Ch. 3), and it is *very likely* that heatwaves will increase in frequency, severity, and duration as warming continues. Figure 2.11a shows projected changes in the number of days at or above 95°F at a global warming level of 2°C. In addition to changes in the number of hot days, multiday heatwaves are *very likely* to last longer, affect a larger spatial extent, and become more severe, exposing more people and infrastructure simultaneously and for longer periods.[180] By contrast, the number of cold days is projected to decrease (Figure 2.11b). Nighttime temperatures are *very likely* to increase faster than daytime temperatures, leading to an increase in extreme nighttime temperatures as the global warming level increases (Figure 2.11c). Such changes in extreme heat are *very likely* to have negative impacts on human health (Ch. 15) and agricultural productivity (Ch. 11).

Projected Changes to Hot and Cold Extremes at 2°C of Global Warming



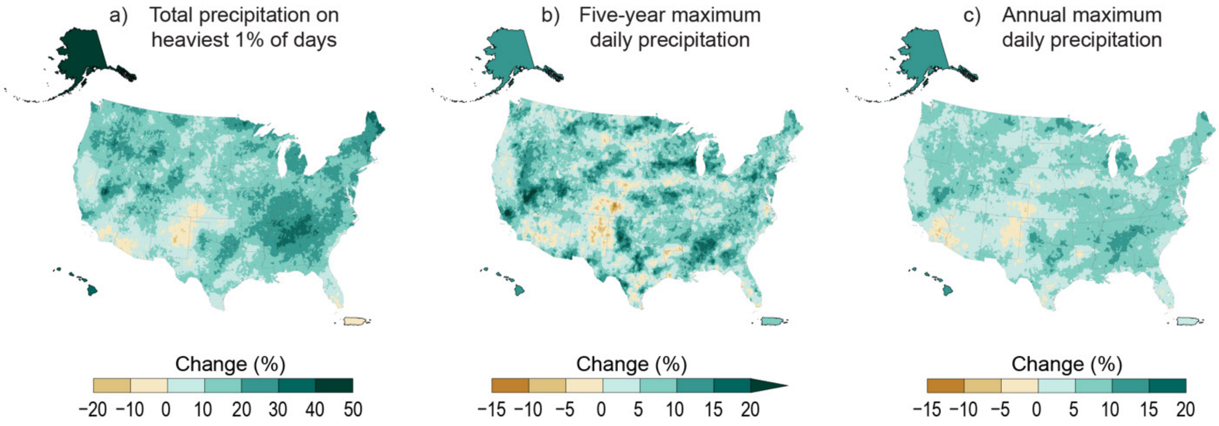
More hot days, even more warm nights, and fewer cold days are expected at a global warming level of 2°C.

Figure 2.11. These maps show changes in the (**a**) projected number of hot days with a maximum temperature at or above 95°F, (**b**) cold days (minimum temperature at or below 32°F), and (**c**) warm nights (minimum temperature at or above 70°F) at a global warming level of 2.0°C. Changes are relative to the period 1991–2020. Based on LOCA2/STAR. Values for Alaska, Hawai‘i, and Puerto Rico are averages from STAR downscaling of 44, 15, and 31 stations, respectively. The Hawai‘i value for cold days is for Mauna Loa, the only network station where freezing temperatures occur. Areas of no change (shown in white) generally will not experience temperatures exceeding those thresholds. Data were not available for the US-Affiliated Pacific Islands and the US Virgin Islands. Figure credit: NOAA NCEI and CISESS NC.

The Frequency and Severity of Heavy Precipitation Increases with the Global Warming Level

Extreme precipitation–producing weather systems ranging from tropical cyclones to atmospheric rivers are *very likely* to produce heavier precipitation at higher global warming levels.[127,181,182,183,184] Recent increases in the frequency, severity, and amount of extreme precipitation are expected to continue across the US even if global warming is limited to Paris Agreement targets.[126,185] Figure 2.12 shows *likely* changes at a GWL of 2°C. Changes in extreme precipitation events differ seasonally—they are *very likely* to increase in spring and winter across CONUS and Alaska and in eastern and northwestern states in the fall, while projected changes in the summer season are more uncertain.[186]

Projected Changes to Precipitation Extremes at 2°C of Global Warming



Increases in the frequency and severity of heavy precipitation are expected at a global warming level of 2°C.

Figure 2.12. The maps show projected changes in three measures of extreme precipitation at a global warming level of 2°C: (**a**) total precipitation falling on the heaviest 1% of days, (**b**) daily maximum precipitation in a 5-year period, and (**c**) the annual heaviest daily precipitation amount. Changes are relative to the period 1991–2020. Based on LOCA2/STAR. Values for Alaska, Hawai‘i, and Puerto Rico are averages from STAR downscaling of 45, 16, and 31 stations, respectively. Data were not available for the US-Affiliated Pacific Islands and the US Virgin Islands. Figure credit: NOAA NCEI and CISESS NC.

Warming-Driven Changes to the Water Balance Affect Drought Risk

Even as downpours increase, the risk of drought is also projected to rise with the global temperature. The past may provide insight into what could happen as temperatures rise. Paleoclimate datasets show that the already-water-stressed Great Basin region, which includes Nevada, parts of Utah and Wyoming, and much of the Southwest, experienced severe drought throughout the mid-Holocene (approximately 5,000–9,000 years ago), when the western Pacific was warm, Arctic temperatures were high, and there was less sea ice—all global changes that are projected in a future warmer world.[187] In the Southwest, multidecadal soil moisture droughts analogous to or drier than the 2000–2021 drought are projected to increase in the future, regardless of global warming level (Ch. 28).[188] This is due to projected decreases in springtime precipitation and earlier snowmelt that, combined with warmer temperatures, push the region into a new and drier average state.[140] However, the risk of single-year droughts analogous to the driest recent year (2002) depends strongly on the global warming level, increasing by 8% at a GWL of 2°C but by 24% at 4°C.[188] Limiting global warming would also reduce the severity of inevitable multidecadal droughts by reducing the magnitude of extreme single-year droughts during these events.

Other regions of the country are not projected to aridify to the same extent as the Southwest. However, projected changes in the amount, type, and timing of precipitation and evapotranspiration will affect the balance of water supply and demand, shaping drought risk in a warmer world. Springtime runoff from snowmelt is projected to decrease with warming in the northern and western regions of CONUS.[189] In the southern and eastern regions of the country, projected increases in winter and spring precipitation will increase moisture availability at the time soils are wettest, leading to higher runoff and flooding risk.[138] Drying of surface soils is projected to occur nearly everywhere; drying increases with the GWL due to increases in evaporative demand with warming. Deeper soil moisture projections are more uncertain,[190] but it is *likely* that total column soil moisture in the Southwest and parts of the Southern Great Plains will become drier with warming.[138]

As the Planet Warms, Storms Become More Dangerous

There is increasing evidence that a warming planet will alter the characteristics and impacts of several storm types. With every increment of global warming, projected sea level rise is *very likely* to lead to higher storm inundation levels when storms do occur (Ch. 9). Projected increases in atmospheric water vapor are *very likely* to lead to more extreme rainfall rates (Ch. 3). Projected increases in water temperatures are *very likely* to result in stronger tropical cyclones globally, with winds 5% faster (3% for the Atlantic basin) at a GWL of 2°C. It is *likely* that the overall global frequency of tropical cyclones will decrease, while the frequency of Category 4–5 hurricanes is *likely* to increase.[183] Recent research points to continued uncertainty in the future frequency of Atlantic hurricanes (e.g., Sena et al. 2022;[191] Knutson et al. 2022[192]), landfall behavior, (e.g., Zhang et al. 2020;[193] Jing et al. 2021;[194] Knutson et al. 2022[192]) and associated hazards (e.g., Gori et al. 2022[195]), as well as possible shifts to increased tropical cyclone activity in the Central Pacific (Ch. 30).[192]

Even in regions that experience an overall decrease in precipitation, atmospheric rivers are projected to become stronger and wider,[184,196] increasing the risk of downpours and floods across the western United States.[181,184,197,198] In addition, the paleoclimate record shows that the locations along the Pacific Coast where storms bring moisture may also shift with warming.[199]

It is *likely* that the frequency of weather environments that give rise to severe thunderstorms in the United States during spring and fall will increase under stronger warming scenarios.[200,201] These changes are *likely* to lengthen the severe thunderstorm season as the world warms, especially in the Midwest and Southeast during cool-season months.[202]

Warming Increases the Risk of Compound Extreme Events

The increasing risk of many individual extreme weather and climate events with warming also increases the risk that multiple extreme events may occur in quick succession in the same region. Warming also increases the risk of multiple extremes occurring simultaneously across multiple regions that are interconnected or interdependent (Focus on Compound Events). Co-occurring hot and dry conditions are projected to become more frequent with warming.[156,203,204] These conditions increase the risk of extreme wildfires, as well as affecting agriculture, water resources, and freshwater and marine ecosystems.

Co-occurring hot and moist conditions are also projected to increase with warming, and the risk of single and multiday humid-heat heatwaves across the densely populated Northeast, Southeast, and parts of the Southwest are projected to increase.[205] Higher temperatures combined with rising humidity due to the increased atmospheric moisture content are contributing to increases in humid-heat extremes—conditions that limit the ability of the human body to naturally cool down that are associated with reduced labor productivity and compounding heat-related health impacts.[206,207]

The combination of increasing drought risk and extreme precipitation are *likely* to increase the risk of extreme wildfire seasons that are followed shortly thereafter by heavy precipitation across the West,[208] which could increase the risk of postfire hazards such as debris flows, landslides, and flash floods similar to those that have affected parts of the region in recent decades (Ch. 4; Figure 3.13). The largest increases are expected in the Pacific Northwest, where this risk has historically been low.[208] Increases in hydroclimate volatility may also affect the Caribbean, Hawai‘i, and some Pacific Islands (Chs. 23, 30). As global temperatures increase, the Atlantic and Gulf Coasts are projected to experience increases in compound flooding from rising sea levels that cause higher storm surge from stronger storms and heavier precipitation that result in runoff and flooding, impacting people, ecosystems, and infrastructure along the coastlines (Ch. 9).[195,209] The scientific understanding of such events continues to evolve (Focus on Compound Events).

Warming Causes Long-Term Sea Level Rise

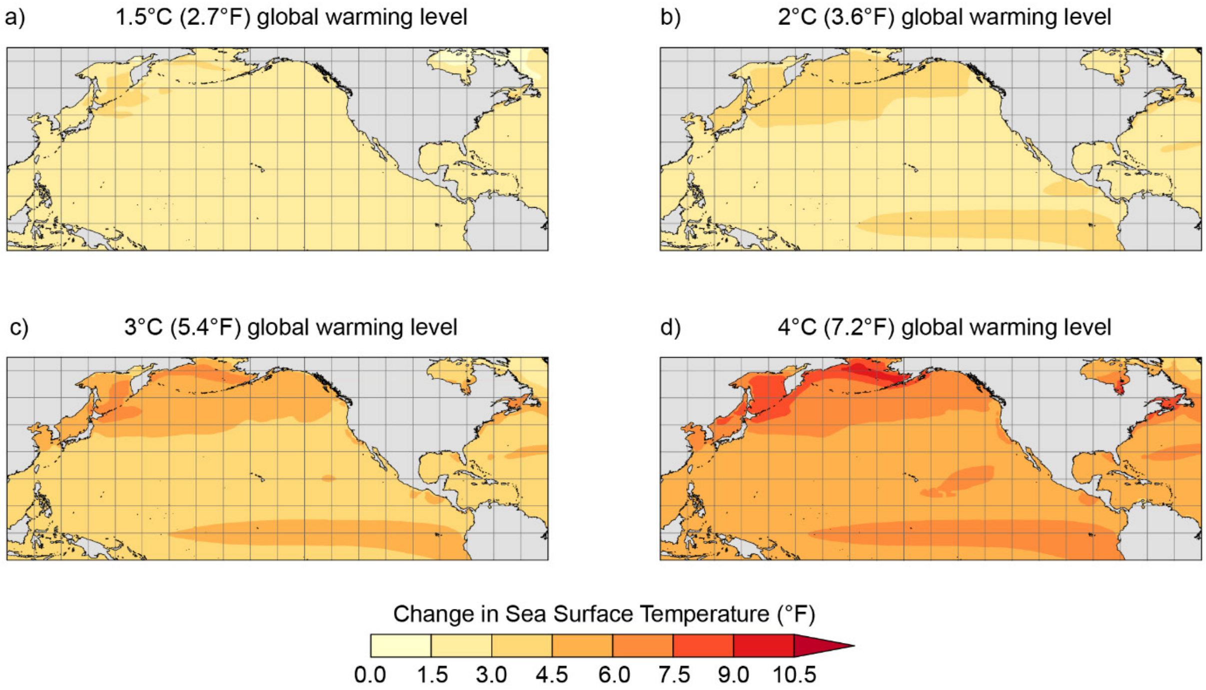
The most substantial differences in projected sea level rise for the United States for different global warming levels begin to arise at the end of this century, due to uncertainty in how much and how quickly ice will be lost from the Antarctic ice sheet.[210,211] A GWL of 2°C would lead to a *likely* sea level rise in CONUS of 2–3 feet in 2100 and 2.5–5 feet in 2150, relative to 2000 sea levels. Every additional degree Celsius of global warming is *likely* to cause at least 4 inches of additional sea level rise in CONUS in 2100 and at least 7 inches of additional sea level rise in 2150 (see Ch. 9 and Figure 9.2 for sea level projections in terms of global warming levels).[67] At a 2°C GWL, sea level rise in CONUS is not expected to exceed 4 feet in 2100 and 7 feet in 2150, although it is not considered impossible. At higher GWLs, such extreme sea level rise becomes more likely within the next 100–150 years.

The total rise in sea level that will be realized beyond 2150 can differ by many feet depending on global warming levels over the next 50–100 years due to the potential for rapid and irreversible loss of ice from Greenland and Antarctica starting next century.[102,212,213] Such significant changes at 2100 and beyond translate directly into substantially increased frequency of flooding events in coastal regions, making major flooding events in some regions as common in 2100 as minor flooding events are currently.[67] However, there are also many processes that drive local variations in sea level rise that are not clearly related to global warming levels, such as vertical land motion. To aid in planning for uncertain future sea level rise, projections are also commonly used to construct sea level scenarios,[67] which are discussed in more detail in Chapter 9 and Appendix 3.

Global Warming Changes the Oceans

Sea surface temperatures increase with the global warming level, but changes are not uniform across the globe: northern oceans are expected to warm faster than the tropics (Figure 2.13). Heat will continue to accumulate in the shallow and deep oceans: at a GWL of 4°C, ocean waters off the West Coast and Alaska could accumulate 3 billion joules per square meter, the Atlantic Coast 5 billion joules per square meter, and the Gulf of Mexico up to 6 billion joules per square meter—roughly the energy equivalent of two hundred pounds of TNT per square foot. As a result, the risk of marine heatwaves is projected to increase as the world warms. Projections indicate an increase of between 150 and 300 marine heatwave days per year if the GWL reaches 2.5°C. It is therefore possible that the coastal oceans of the United States could enter into near-permanent heatwave status, with significant ramifications for marine life.[214] The probability that September sea ice completely disappears from the Arctic Ocean, including Alaska coastal waters, rises from 1% in 2100 under a GWL of 1.5°C to 10%–30% at a GWL of 2°C.[79]

Projected Changes to Sea Surface Temperatures at 1.5°C, 2°C, 3°C, and 4°C of Global Warming



At higher global warming levels, sea surface temperatures are projected to change around the US coasts and open ocean, with implications for marine resources in those waters.

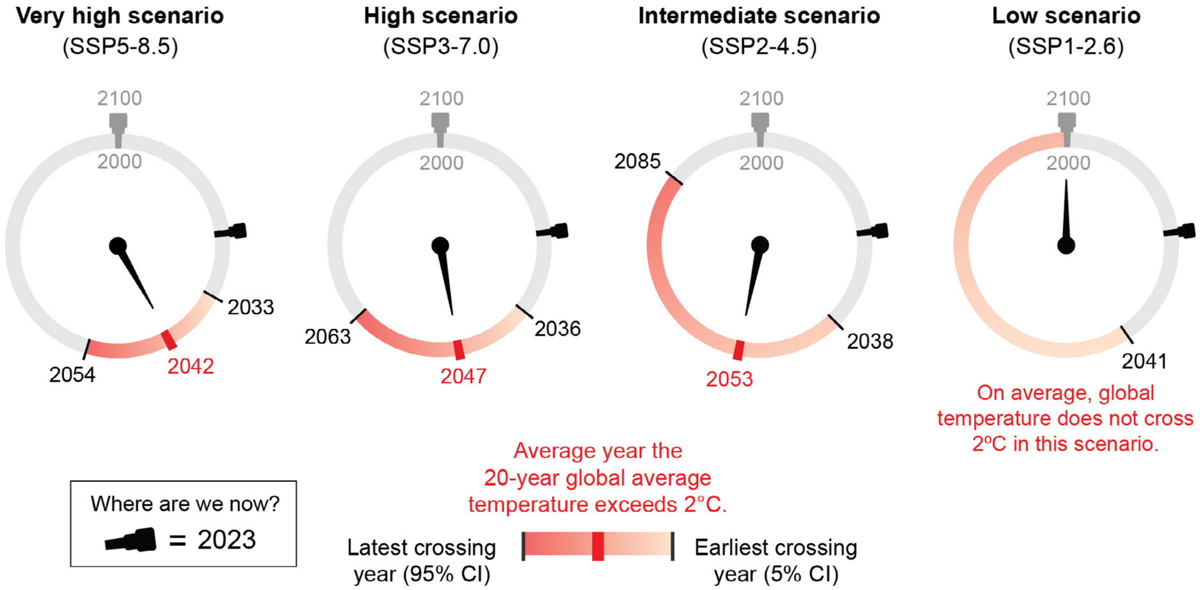
Figure 2.13. These maps show projected changes in sea surface temperatures (°F) for various global warming levels (1.5°, 2.0°, 3.0°, and 4.0°C). Changes are relative to the period 1851–1900. Figure credit: NOAA, NOAA NCEI, and CISESS NC.

Projected changes in ocean acidification and oxygen loss in US waters vary with location. For higher levels of future CO_2 emissions, the chemistry of waters in the Gulf of Maine will change in ways damaging to shell-building organisms, with the saturation level of aragonite—a form of calcium carbonate used by shell-building marine life—projected to fall below a crucial shell-building threshold for most of the year.[215] Ocean oxygen loss in the upper and middle depths will be most pronounced for the United States in the North Pacific, including off the coasts of Alaska and the Pacific Coast, which will squeeze the habitats of marine life moving away from warming waters at the surface.[216,217]

When or If We Reach a Particular Global Warming Threshold Depends on Future Emissions

Projections of future global average surface temperature primarily depend on two things: 1) future emissions (Ch. 32) and 2) how sensitive the climate system is to these emissions (KM 3.2). In a very high scenario, the world is *very likely* to exceed a global warming level of 2°C between 2033 and 2054, depending on the climate sensitivity to greenhouse gas emissions (Ch. 3). In a low scenario, by contrast, the world is *very likely* not to cross this threshold at all (Figure 2.14). In addition to warming more, in high and very high scenarios, the Earth warms faster. The occurrence of some record-shattering extremes is dependent on this rate of warming.[218] Faster climate change also increases the challenge of adaptation for both human and natural systems.

Projected Global Surface Temperature Change



Future emissions of greenhouse gases determine whether and how quickly we reach 2°C of global warming.

Figure 2.14. When (or if) the world reaches 2°C of global warming depends on future greenhouse gas emissions and the sensitivity of the climate system to those emissions. Shown are the IPCC AR6 assessed warming projections for four future scenarios, with projected years at which the 2°C (3.6°F) global warming level would be reached. For example, under a very high scenario (SSP5-8.5), models project reaching 2°C between 2033 and 2054, with an average estimate of 2042. Under a low scenario (SSP1-2.6), the 5% CI (confidence interval) range begins at 2041, but the average projection shows that warming would actually stay below 2°C. Figure credit: Project Drawdown, Stripe Inc., NOAA NCEI, and CISESS NC.

Over the past few years, a number of analyses have narrowed the plausible range of current emissions outcomes based on policies in place today (see existing US mitigation policies by state, Figure 32.20), putting the world on track for a central warming estimate of around 2.6°C (ranging from 2°–3.7°C) by 2100.[219,220,221,222,223,224] Existing climate pledges, if implemented, would increase the likelihood of limiting temperature change to well below 2°C.[225] To achieve more ambitious targets, stronger action would be needed. Emissions from existing and currently planned fossil fuel infrastructure globally would put the planet on a trajectory to exceed 1.5°C in the coming decades.[226] However, current policy projections represent neither a ceiling nor a floor on future climate outcomes. Our choices matter: global surface temperatures will continue to rise until CO_2 emissions reach net zero, and surface temperatures are not expected to fall for centuries in the absence of net-negative emissions. At the same time, Earth system models suggest that only a small amount of additional surface temperature change is expected over the next few centuries if CO_2 emissions reach net zero and there are deep reductions in other greenhouse gases, at least under scenarios where global warming is limited to 2°C or below by 2100.[227] In other words, additional warming over the next few centuries is not necessarily “locked in” after net CO_2 emissions fall to zero.

Some Impacts Are Inevitable Because of Past Choices

While most models project that the Earth will stop warming if CO_2 emissions reach net zero, an end to warming does not imply an end to climate change. Because the CO_2 not removed by sinks on land and in the ocean remains in the atmosphere for thousands of years, the accumulation of past emissions already makes some impacts inevitable, regardless of future mitigation actions. Certain slow-moving aspects of the climate system such as ice sheets and the deep ocean take decades or centuries to respond to changes. This means that even in a low scenario where global warming slows or stops, some climate changes will continue as the Earth continues to adjust.

Some Ocean Changes Are Locked In Even Under Aggressive Mitigation Scenarios

Past emissions will continue to affect the ocean for thousands of years. Regardless of future emissions, the surface ocean will continue to take up heat from the atmosphere, accumulating 2–4 times as much heat as has been taken up since 1970, even under low or very low scenarios.[79] This heat will have cascading effects on marine ecosystems, increasing the probability of marine heatwaves and causing sea level rise due to the expansion of warm water. Even after the world reaches net-zero emissions, oceans will continue to acidify as they gradually absorb the atmospheric CO_2 produced by past human activities.

Sea Level Will Continue to Rise

Sea level along US coastlines is expected to continue rising regardless of global warming levels for the foreseeable future (at least for hundreds of years). Under a range of potential global warming levels, average sea level along US coastlines is *likely* to be between 12 and 20 inches above 2000 sea levels in 2050 (Figure 9.2).[67,88] At these short timescales, regional variations in projected sea level rise are large, with 4–12 inches of sea level rise *likely* in the Pacific Northwest and 20–27 inches of sea level rise *likely* in the western Gulf of Mexico. On timescales relevant to infrastructure planning (the design life of infrastructure ranges from 10 to more than 100 years), rates of sea level rise are also expected to continue accelerating under all but the lowest potential global warming levels (greater than 2°C).[67] Future projected changes in sea level will *likely* lead to an increased frequency of coastal flooding events in the continental United States over the next 30 years, with a greater-than-tenfold increase in typically damaging flooding events (e.g., storm surge currently recurring every few years) and a fivefold increase in destructive flooding events (e.g., major storm surge events currently recurring once in many decades) over this time period.[67] The onset of enhanced flooding frequency in coastal areas depends not only on the local trend in sea level but also low-frequency tidal cycles[228] and remote modes of natural climatic variability (e.g., ENSO, the Pacific Decadal Oscillation, and the North Atlantic Oscillation).[229]

Adaptation to a Changing Climate Will Be Necessary

It is not possible to prevent climate change: the current global warming level is already over 1.1°C. The US, across all levels of government, business, and civil society, must both adapt to this reality of a changing climate and prepare for at least some level of additional warming. Inertia in the world's infrastructure[230] and economic and political systems[231] means that the near-term trend in risk over the next few decades is largely independent of the choice of emissions scenario,[224] and the climate benefits of aggressive action to reduce greenhouse gas emissions are unlikely to be realized in the near term. The faster and more extensive the warming, the greater the risk of climate impacts overtaking the speed of adaptation (KM 4.3), as there are both barriers and limits to adaptation (Ch. 31; KM 31.2). This means the US will need to adapt to a changing climate regardless of future emissions.

We Cannot Rule Out Catastrophic Outcomes

Climate Sensitivities Exceeding 4°C Are Unlikely but Not Impossible

There is no known precedent for a species changing its own climate as quickly as humans are changing ours, and there are many uncertainties associated with a rapidly warming world. Low-probability and potentially catastrophic outcomes are not impossible, and these risks persist even under current policies. While recent assessments (KM 3.2)[232] put the *likely* range of equilibrium climate sensitivity—the long-term warming the world will experience if atmospheric CO_2 concentrations are doubled—between 2.5°C and 4.0°C, higher values are not definitively ruled out, and feedback loops such as changes to cloud cover may lead to more warming in the future. Similarly, we cannot rule out a GWL of 4°C or more this century, particularly if climate change strongly reduces the ability of the biosphere or ocean to remove carbon from the atmosphere (Ch. 3).

Changes to the Carbon Cycle May Increase the Amount of CO_2 Remaining in the Atmosphere

Our emerging understanding of land, ocean, coastal, and freshwater systems suggests the possibility of a decline in future carbon uptake capacity among both land and ocean ecosystems.[233,234,235] The balance of carbon uptake and release across terrestrial ecosystems depends on the relative balance of photosynthesis, respiration, and decomposition, which in turn strongly depends on temperature and moisture availability. Changes in either can alter the balance of carbon uptake and release across terrestrial ecosystems (Ch. 7). Similarly, the rate and extent to which atmospheric CO_2 is exchanged with ocean and freshwater systems is controlled by a combination of temperature, salinity, pressure, upwelling, and biological consumption and release of CO_2.

Although net land and ocean carbon sinks have increased in response to increased carbon emissions over the past six decades,[33,233] climate models project that the fraction of emissions taken up by land and oceans will decline, albeit with significant differences in regional responses and underlying mechanisms driving those responses.[1,236] For example, land reservoirs, such as tropical forests or the Arctic–boreal ecosystems, could switch from a net sink to a net source of carbon to the atmosphere (e.g., Huntzinger et al. 2018[234]).

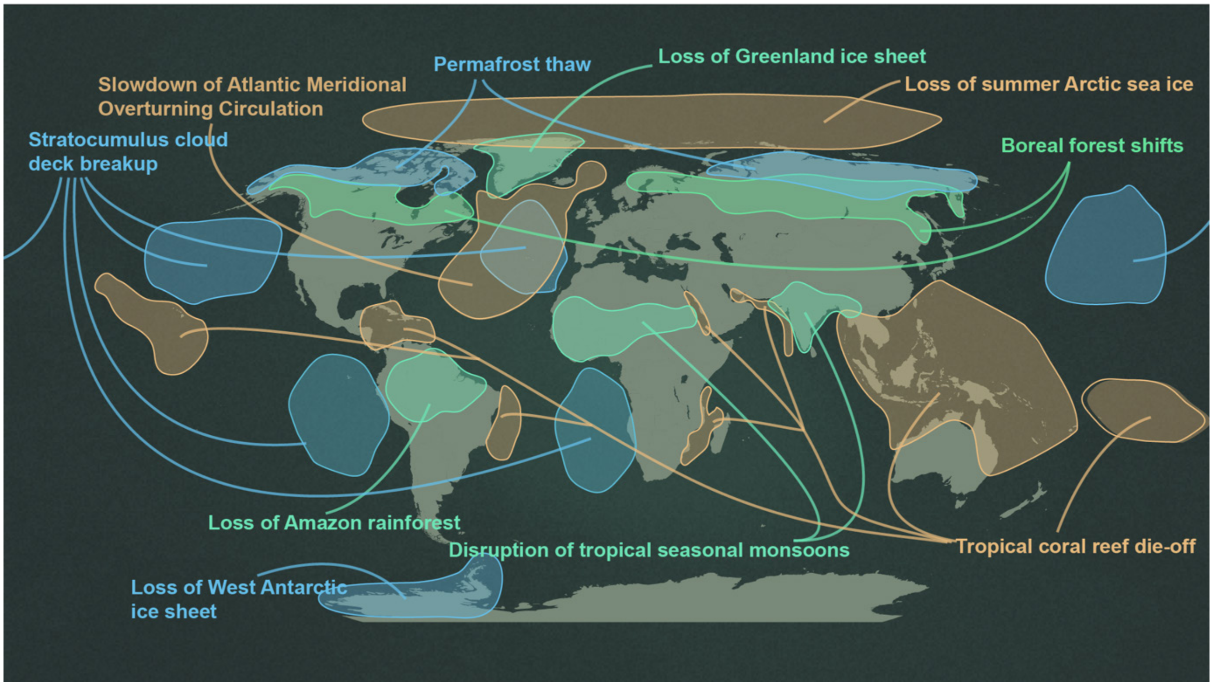
The Arctic–boreal region (Ch. 29) is particularly vulnerable to future climate change and rising temperatures, which could lead to the release of vast amounts of carbon from thawing permafrost, along with changes in vegetation productivity and disturbances such as wildfires and insect outbreaks. There is estimated to be about 4.8–5.9 trillion tons of carbon[237] frozen down to 20 meters in Arctic permafrost. This is roughly double the amount currently in the atmosphere and more than three times what already has been emitted to the atmosphere from fossil fuel use since preindustrial times. With rising temperatures and thawing soils, some of these carbon deposits may be mobilized to the atmosphere, primarily as CO_2. More than one hundred billion tons of CO_2 are *likely* to be released by thawing permafrost over the next century, with higher-end estimates of around 400 billion tons.[238] The total carbon emissions from thawing permafrost are expected to exceed the carbon captured by increases in vegetation productivity.[238] A smaller fraction of permafrost carbon will be emitted as the more powerful greenhouse gas methane. Methane emissions are projected to cause 40%–70% of total permafrost-affected radiative forcing in this century.[239]

Tipping Elements Could Lead to Regional Rapid Changes

Tipping elements, or tipping points as they are colloquially known, are components of the Earth system that may respond to human-caused climate change by transitioning toward substantially different long-term states upon passing key thresholds.[240] In some cases, such changes could produce additional greenhouse gas emissions that could compound global warming.[241,242,243]

Systems that have been identified as possible tipping elements include the slowdown of the Atlantic Meridional Overturning Circulation, Arctic permafrost thaw, loss of the Greenland and West Antarctic ice sheets, Arctic sea ice loss, boreal forest shifts, disruption of tropical seasonal monsoons, Amazon rainforest dieback, tropical coral reef loss, and the disappearance of clouds that currently reflect sunlight cooling the Earth (Figure 2.15).[91] While some of these tipping elements are represented in modern Earth system models, many are still not, and the precise response of these systems to rapid climate change remains poorly understood. It is not possible to say that exceeding a particular GWL will trigger these tipping elements, nor are scientists certain that staying below a particular GWL will prevent them. However, the risk of these nonlinear changes increases with every increment of global warming.

Possible Regional Tipping Elements



Continued warming could push some aspects of the Earth system past tipping points.

Figure 2.15. The figure shows 10 potential tipping elements in the climate system. These include changes to tropical and boreal forests and coral reefs, the loss of Greenland or West Antarctic ice sheets, and changes to the circulation of the oceans and the monsoons. The spatial area affected by each tipping element is shown; colors are used for visual clarity. Adapted with permission from Figure 1 in Wang et al. 2023,[240] which was adapted from McSweeney 2020.[244]

Extreme Sea Level Rise Cannot Be Ruled Out

Increases in sea level along the continental US coast of 3–6 feet by 2100 and 5–12 feet by 2150, depending on human emissions, are distinct possibilities that cannot be ruled out (i.e., they have at least 1% chance of occurrence with global warming levels of 1.5°–4°C).[67,102,210] Beyond 2100, there is still substantial uncertainty in projected sea level rise under the most extreme scenarios of future warming and ice sheet mass loss.[210] This long-term uncertainty is primarily related to persistent gaps in our understanding of how glacier ice flows and fractures,[245,246,247] how snowfall changes under warming,[248] and how melt water behaves on the ice sheet surface.[249,250] Recent progress in better quantifying the uncertainties in the ice sheet contribution to future sea level projections[212,251] and ensuring that models accurately capture past ice sheet behavior[103,252] indicate that ice sheet models are quickly becoming better suited to produce usable and credible sea level projections. Continued model development can reduce uncertainty in the likelihood of extreme sea level rise scenarios. In particular, there is strong incentive to continue reducing uncertainty surrounding the tail risks associated with potential low-likelihood but high-impact sea level rise projections past 2100, as planning for catastrophic outcomes makes adaptation much more costly.[253,254]

The Biggest Uncertainty Is What We Will Do

Despite uncertainties in how land, ocean, atmosphere, and ice will respond to warming, and despite internal variability in the climate system, the largest source of uncertainty is the trajectory of our greenhouse gas emissions (KM 3.3). This is within human control and depends on our collective policy, economic, and social choices (Ch. 32). Although we probably will not be able to detect climate benefits from even the most aggressive possible emission reductions before the middle of the century, given the magnitude of internal climate variability, there are numerous co-benefits to mitigation in the near term, including improvements to air quality and health, reductions in mortality, and benefits to agriculture, the economy, and the labor market (KM 32.4).[14]

Human efforts to achieve rapid reductions in emissions can still limit global temperature changes to well below 2°C.[222] Global temperatures can be limited to 1.5°C above preindustrial levels by 2100 in scenarios where global CO_2 emissions reach net zero in the middle of this century alongside deep cuts to methane (KM 32.2) and other short-lived climate pollutants, with modest deployments of net-negative emissions thereafter.[255] Most of these scenarios have at least some midcentury temperature overshoot, however, which could result in irreversible consequences to global ecosystems (Ch. 8).[256] Still, the degree to which climate change will continue to worsen is in large part up to humans. The drastic emissions cuts required to stabilize global climate are possible (KM 32.1) and can be achieved in ways that are sustainable, healthy, and fair (KM 32.4). If emissions do not fall rapidly, the risks of extreme weather, compound events, and other climate impacts will continue to grow. How much more the world warms depends on the choices societies make today. The future is in human hands.

Traceable Accounts

Acknowledgments

The authors would like to thank Talia Resnick and Annika Larson for research assistance, including discussions about report structure, literature review, and bibliography management.

Process Description

Most team members were selected from the pool of nominations received via the public call for authors; others were identified through extended networks to ensure diverse representation across multiple axes. The following areas of expertise were identified as crucial for Chapter 2:

- Paleoclimate and long-term context for climate trends
- Carbon cycle observations and greenhouse gases
- Infrastructure and resilience scenarios and projections in the CMIP6 (Coupled Model Intercomparison Project, Phase 6) models
- Regional trends
- Hurricanes, tropical cyclones, and midlatitude storms
- Ocean trends
- Cryosphere and sea level rise
- Climate extremes
- Diverse leadership in science
- Observations of climate trends

Author meetings were held virtually biweekly. Consensus was built by referring to the literature and leveraging the specific expertise of chapter authors. Engagement with other chapters occurred through formal presentations at the April 2022 chapter leadership meeting and one-on-one meetings between chapter lead authors.

Key Message 2.1

Climate Is Changing, and Scientists Understand Why

Description of Evidence Base

The evidence base for human-caused increases in greenhouse gases (GHGs) is extensive and includes satellite and ground-based observations, solid theoretical understanding, and coherent measurements across multiple systems. Evidence for changes in aerosols includes long-term satellite and ground-based observations. Evidence for warming and other long-term climate changes has been extensively documented across multiple variables. Observations at smaller scales are noisier and regional signals more difficult to separate from natural internal climate variability.

Observational surface temperature records are available from a wide variety of scientific groups (e.g., Hansen et al. 2010;[2] Vose et al. 2021;[5] Morice et al. 2021;[3] Rohde and Hausfather 2020[4]). These temperature records combine land surface temperature data from weather stations with ocean sea surface temperature records from sources including ships and buoys. These records are corrected for inhomogeneities introduced by changes in measurement techniques over time and use various different interpolation techniques to estimate temperature anomalies between measurement locations.

Long-term changes have been observed in many other aspects of the climate system. Seasonal average and extreme precipitation changes are widely documented using observations, and changes are consistent with our physical understanding. The evidence base for ocean changes includes long-term surface and subsurface ocean observations of temperature, salinity, oxygen, and pH in the coastal and open ocean and satellite data.

Paleoclimate evidence includes multiple proxy-based reconstructions and modeling.

Sea level rise over the industrial era has been measured with local tide gauges and satellite altimetry (since the 1970s). Changes in the processes contributing to sea level rise (ocean thermal expansion, glacier and ice sheet melt, and terrestrial freshwater discharges) have been independently measured using in situ techniques in the ocean (e.g., floats, ship-based measurements) and on ice sheets, as well as remotely (e.g., satellite gravimetry and interferometry). Changes in sea ice and lake ice over the past several decades at the poles have been extensively documented from satellites, including visible imagery, altimetry, and microwave backscatter.

Drought has many definitions including meteorological drought, agricultural drought, snow drought, and soil moisture drought; soil moisture projections depend on depth, with surface layers more responsive to short-term temperature changes, while deeper root-zone moisture changes on longer timescales. Moreover, drought can be defined on timescales ranging from several weeks to multidecadal megadroughts. The level of uncertainty in drought changes in several regions depends on the definitions and metrics used and the sources of measurements. Surface-based measurements of soil moisture are limited, and reliable satellite-based measurements of soil moisture are less than a decade long.

Major Uncertainties and Research Gaps

Uncertainty in Global Surface Temperature Reconstructions

In recent years, different groups producing global surface temperature records have somewhat converged in methodological approach, drawing on a larger set of collected weather station data[257,258] and using more granular interpolation approaches rather than simple latitude/longitude grid-cell averaging.[5] Published global surface temperature uncertainties on an annual basis range from ±0.13°C to ±0.2°C in the 1850s when records are more sparse to ±0.03°C to ±0.09°C at present across different surface temperature datasets, with differences between datasets driven by the number of measurements included, the spatial interpolation approach, and the method of uncertainty calculation.[4]

Uncertainty in GHG Emissions Estimates from Inventories and Models

GHG emissions estimates are typically derived using either a “bottom-up” or a “top-down” approach.[259,260] The bottom-up approach uses a combination of activity data and emissions factors alongside empirical or process-based models to estimate the flux exchange between the different compartments of the land–ocean–atmosphere system. A primary advantage of the bottom-up approach is that it allows for explicit characterization of emissions and removals into specific sectors identified in the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories.[79,261] However, bottom-up emissions estimates can have significant uncertainty when the activity data or emissions factors are not well quantified or when process-based models are not well characterized due to missing processes or uncertain parameterization. On the other hand, the top-down approach aims to utilize the information from atmospheric greenhouse gas observations and atmospheric transport model to infer information about the distribution of emissions and removals at the surface of the Earth. For example, recent advancements in atmospheric CO_2 observations from satellites and top-down modeling approaches have allowed insights into CO_2 emissions and removals at the national scale.[262] However, uncertainties in the modeling framework, spatial and temporal observational gaps, and uncertainties in the data may result in large uncertainties in the emissions estimates derived from the top-down approaches. Within the larger carbon cycle science community, various efforts are underway (e.g., REgional Carbon Cycle Assessment and Processes, Phase 2) to increase the level of agreement between estimates from these two approaches, thereby yielding more robust knowledge of GHG emissions.[263]

Uncertainty in Arctic Connections to Midlatitude Weather Extremes

Uncertainties in the influence of the Arctic on midlatitude weather extremes remain due to lack of consistency in model responses and observations, particularly for the winter season. Several advances in the physical understanding of how Arctic processes could influence midlatitude extremes in various seasons have been made since the publication of the Fourth National Climate Assessment,[264] yet the mechanisms continue to be a subject of debate in the scientific community.

Uncertainty in Drought Projections and Definitions

Drought projections are complicated by definitional ambiguity and the use of many standard metrics. For example, there is ambiguity in the definition of "flash drought," with more than 20 unique definitions present in the literature.[265] Moreover, agricultural drought depends not just on precipitation and temperature but also on evaporation and transpiration from the land surface—processes that are projected to change in a warmer world (Ch. 3). Metrics such as the standardized precipitation index or the Palmer Drought Severity Index that rely on meteorological values may yield different projections than indices that take into account land changes (such as precipitation minus evaporation).[266]

Description of Confidence and Likelihood

It is unequivocal that global temperatures are increasing, and scientists are *virtually certain* that the planet has warmed between 1.1° and 1.2°C since the beginning of the industrial revolution, based on multiple observational datasets. There is *very high confidence* that this warming is driven by human-caused GHG emissions, which have increased by over 47% since 1850 based on modeling studies and theoretical understanding. There is *very high confidence* that changes outside the boundaries of the United States affect the Nation's climate because scientists understand the mechanisms by which melting in Antarctica and Greenland affect sea level in the US.[67] The links between tropical warming and atmospheric river intensity are due to well-understood atmospheric thermodynamics.[98,99] A wide range of detection and attribution studies (discussed in Ch. 3 and summarized in Eyring et al. 2021[267]) establish that long-term changes due to climate change have been observed in many aspects of the climate system.

Key Message 2.2

Extreme Events Are Becoming More Frequent and Severe

Description of Evidence Base

Extreme events are rare by definition, but multiple datasets[125,268] indicate they are increasing. The authors have a solid theoretical understanding of how some events (heatwaves, downpours) should increase in a warming world (Ch. 3). Others (e.g., agricultural drought) depend on multiple interacting physical processes.[190,269] Event attribution now allows us to assign a quantifiable fraction of attributable risk to climate change (Ch. 3).

A wide variety of observational evidence exists for the occurrence of different storm types. Trained weather observers and storm spotters create storm reports across the country for severe hail, winds, and tornadoes. The National Weather Service (NWS) WSR-88D radar network maintains nationwide surveillance observations of precipitation, winds, and storm occurrence. The NWS additionally conducts storm damage surveys for high-impact events. NOAA and Air Force Hurricane Hunters conduct surveillance flights into tropical cyclones expected to impact US interests. NOAA geostationary satellite observations maintain a record of cloud properties and lightning occurrence. However, the length and representativeness of each data source are variable; storm reporting relates to population density and exposure, and the availability of trained observers impacts record quality, especially for transient phenomena such as hail.

Major Uncertainties and Research Gaps

There is growing evidence that the impacts of climate change are, and will be, distributed unequally across US populations due to differences in both exposure and vulnerability. However, there are gaps in understanding the community-level impacts of projected changes in extreme events. Vulnerability at this level is in part a function of our investments (capital, operations, and management) in the built environment and natural resource functionality that serve to buffer these impacts (e.g., stormwater conveyance and levees to reduce flooding, water storage to relieve water shortages during drought). There is a lack of systematic assessment of these assets and other facets of vulnerability across the United States.

New literature has emerged documenting changes in certain types of compounding extremes such as heat and drought, but the limited observed record hinders quantifying long-term trends in several other compound extremes. Several frameworks for studying various compound extremes have emerged as well, and the physical understanding of certain compound extreme events such as heat/drought, heat/humidity, and coastal wind/precipitation/flooding has been documented, yet the understanding of the physical drivers of many other compound extremes is still emerging. Therefore, there are gaps in methodological advances, advances in understanding of their physical drivers, and studies quantifying projections in compound extreme risks.

The lack of homogenized daily and hourly temperature datasets limits our ability to reliably assess the evolution of extreme heat events over century-scale periods, although the availability of modern reanalysis products has increased agreement in changes in extreme heat events over the past 50 years.

There is limited research on changes in lightning activity due to lack of a long-term observational record. Satellite-based records and lightning detection networks are not sufficiently long to allow for detecting trends. Lightning can pose major hazards to society including direct casualties, igniting wildfires, and damaging energy infrastructure.[167]

Description of Confidence and Likelihood

There is *very high confidence* that heatwaves globally are becoming more frequent and severe, based on multiple observational datasets. In the United States, there is *high confidence* that heatwaves in the West are becoming more common and severe based on observational records since 1901 (Figure 2.7). There is also *very high confidence* that climate change is and will continue to make rainfall extremes more intense. Basic physical understanding and climate models both provide robust explanations for the links between climate change and observed changes in these extremes: this is why the authors also have *high confidence* that storms are delivering more rainfall and *high confidence* that storm surges are becoming higher. There is *very high confidence* that the Southwest is experiencing more severe drought: a recent paper found the 2002–2022 multidecadal soil moisture drought was the worst in the past 1,200 years.[135] The eastern region is experiencing reduced drought risk; studies suggest a transition toward more frequent extremes[141] and indicate that warming may partially counteract the effects of increased precipitation. Other extremes involve more complex interactions between human and natural systems: the occurrence and impacts of wildfires depend on fire ignition and suppression practices. However, while fire risk is not solely determined by climate factors, the authors have *very high confidence* that the hot and dry weather conditions that elevate fire risk are becoming more common.

Key Message 2.3

How Much the Climate Changes Depends on the Choices Made Now

Description of Evidence Base

The Shared Socioeconomic Pathways (SSPs) were made available to the broader research community, replacing the old Representative Concentration Pathways (RCPs) and providing a more detailed assessment of the range of possible emissions pathways, as well as mitigation and adaptation challenges across different sets of socioeconomic assumptions.[270] A subset of the SSPs served as the basis for CMIP6 scenarios used in this Assessment and the Sixth Assessment Report (AR6) of the IPCC.[88]

CMIP6 provides a large set of model runs to use in evaluating different future emissions pathways and global warming levels. In addition, recent work assessing multiple lines of evidence from observational data, paleoclimate evidence, and physical process modeling has helped narrow the range of climate sensitivity.[232] The IPCC AR6 produced a new set of assessed warming projections based on these climate sensitivity estimates and CMIP6 models that were weighted based on their performance in reproducing historical temperatures.

The IPCC AR6 Working Group III[256] report explored a wider range of “overshoot” scenarios, where global temperatures temporarily exceed 1.5°C before being reduced through the large-scale use of negative-emissions technologies. Additionally, AR6 Working Group I provided a thorough exploration of the zero-emissions commitment associated with the cessation of carbon dioxide (CO_2) and other GHG emissions, building off the work of the Zero Emissions Commitment Model Intercomparison Project (ZECMIP).[227]

Recent literature summarized in IPCC AR6 Working Group III[256] and in Hausfather and Moore (2022)[219] provides a clearer sense of expected global average surface temperature outcomes under scenarios including only current policy, near-term 2030 commitments, and long-term net-zero commitments.

Major Uncertainties and Research Gaps

Major uncertainties remain surrounding the emissions trajectories implied by current policies and the plausibility of worse-than-current-policy emissions outcomes. While most current policy scenarios in the literature project relatively flat global emissions over the next few decades, there are some (e.g., in the IPCC AR6 Working Group III scenario database) in which emissions continue to increase. Similarly, large uncertainties remain when translating near-term and long-term mitigation commitments to global emissions pathways, particularly for non-CO_2 GHGs and other climate forcings like aerosols.

The translation from emissions scenarios to warming outcomes is complicated by uncertainties in both the sensitivity of the climate to emissions (both the transient climate response and the equilibrium climate sensitivity) and carbon cycle feedbacks that may affect the portion of emissions that accumulate in the atmosphere. Specifically for carbon cycle feedbacks, it will be the balance between the response of land and ocean systems to future climate that will determine the strength and extent of carbon uptake by these systems, whether they may become a net source of CO_2 to the atmosphere, and, consequently, the trajectory of future GHG forcings.

While recent work[232] has meaningfully narrowed the potential range of climate sensitivity, there are still tail risks of outcomes where equilibrium climate sensitivity exceeds 5°C or is below 2°C per doubling of atmospheric CO_2. There is also disagreement between a subset of high-sensitivity CMIP6 models and other lines of evidence supporting a narrower range of climate sensitivity.[271]

On timescales of less than 50 years, the most significant uncertainties in future sea level are due to regional and local variations in sea level rise and the interannual sea level variability intrinsic to the coastal ocean system. In Alaska and New England, the regional gravitational influence of glaciers and ice sheets may cause lower sea level rise or even sea level fall in the future, although the extent of these gravitational effects is highly dependent on the spatial fingerprint of glacier and ice sheet loss, which is uncertain.[100] Internal variability and human-caused changes in ocean circulation appear to have a strong effect on year-to-year sea level, particularly in the US Mid-Atlantic Coast,[272] but are not consistently simulated between models or included in the range of uncertainty in most sea level projections.[67]

On longer timescales (2100 and beyond), there are substantial uncertainties in projected sea level rise due to an incomplete understanding (and intermodel differences) of how the Greenland and Antarctic ice sheets will behave in a warmer climate. There is a consensus that past carbon emissions and even relatively moderate future global warming levels commit the planet to at least 3–6 feet of sea level rise over hundreds to thousands of years from the melting of the Greenland and Antarctic ice sheets.[273] However, there are many feet of uncertainty remaining both in the already-committed sea level rise and the sea level rise that could be expected under a range of global warming levels.[102,210,274,275] Ongoing research to understand how glaciers and ice sheets flow, fracture, and melt in response to climate change aims to narrow this wide range in sea level rise beyond 2100.

Projections of seasonal and extreme precipitation are widely studied and show more consistent and robust responses in extremes than average changes. The physical process link between higher temperatures and higher moisture availability in the atmosphere is well documented and understood. However, uncertainties remain in our understanding of the response of precipitation-producing systems, particularly those governed by mesoscale processes such as mesoscale convective systems and thunderstorms, which are not directly simulated in global climate models. Uncertainties, especially around how other factors that influence storm development (such as vertical wind shear and atmospheric instability) will change in future climates, link back to model uncertainty and bias at larger scales.

Uncertainty in drought projections arises from these uncertainties in precipitation. Climate models generally project drying in the US Southwest in response to elevated global warming levels, but the precipitation response is highly uncertain. The response of land vegetation also complicates drought projections. Under elevated CO_2 levels, certain types of plants may become more efficient at using water due to a physiological response. This is expected to be at least partially counteracted by greening in response to elevated CO_2 levels. Additionally, the vegetation response to increased heat stress, extreme precipitation, and fire risk is complex and not yet fully understood.

Description of Confidence and Likelihood

There is *very high confidence* that many impacts—both changes to the average state and the risk of extreme events—will intensify as the temperature increases. This is based on physical understanding of the underlying drivers reflected in climate models of varying complexity, including the state-of-the-art general circulation models participating in CMIP6.[276] It is an unequivocal fact, backed by over 100 years of theory and observation, that warming increases with GHG emissions,[277] and warming is *virtually certain* to continue at current levels of emissions. There is *very high confidence* that warming will continue at least until emissions of carbon dioxide reach net zero. The cessation of warming at the point of (net) zero CO_2 emissions (called the zero-emissions commitment, or ZEC) traces back to Matthews and Caldeira (2008),[278] Solomon et al. (2009),[279] and Matthews and Weaver (2010),[280] who were among the first to explore zero-emissions scenarios in emissions-driven climate model runs. The common conflation of constant concentration scenarios with zero-emissions scenarios has led to the misconception that substantial future warming is inevitable. In the lead-up to AR6, there was a desire by the community to further explore the robustness of ZEC results. This led to the creation of ZECMIP, where 18 different Earth system models were used to examine ZEC under a variety of emissions-reduction pathways and cumulative emissions scenarios. ZECMIP broadly found that ZEC was 0°C ± 0.3°C across the Earth system models examined.[227] Hence, rapidly reducing emissions would *very likely* limit future warming (*very high confidence*). It is *very likely* that the eventual global warming in response to a doubling of atmospheric CO_2 is between 2.3° and 4.7°C and *likely* that the warming would be between 2.6° and 3.9°C.[232] There is *high confidence* that catastrophic scenarios where warming exceeds 4°C cannot be ruled out due to uncertainties in climate sensitivity, carbon cycle feedbacks,[239,281] and emissions scenarios.[282]

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