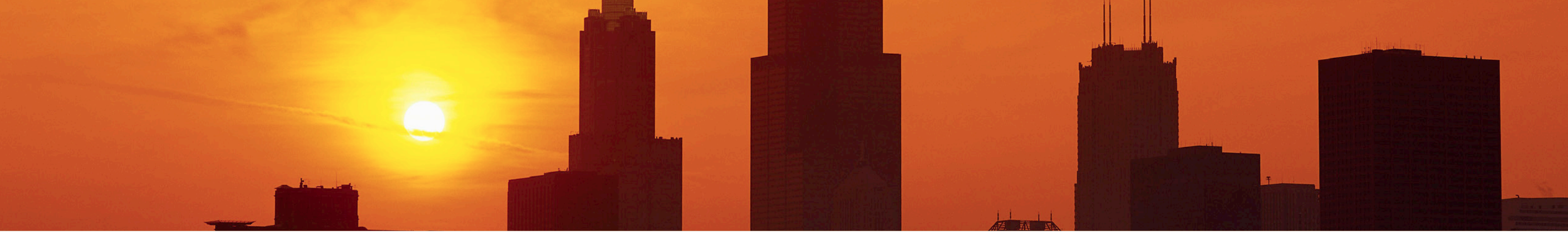

CHAPTER 2
OUR CHANGING CLIMATE

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

2 OUR CHANGING CLIMATE

Key Messages

1. **Global climate is changing and this change is apparent across a wide range of observations. The global warming of the past 50 years is primarily due to human activities.**

2. **Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, and how sensitive the Earth's climate is to those emissions.**

3. **U.S. average temperature has increased by 1.3°F to 1.9°F since record keeping began in 1895; most of this increase has occurred since about 1970. The most recent decade was the nation's warmest on record. Temperatures in the United States are expected to continue to rise. Because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, uniform or smooth across the country or over time.**

4. **The length of the frost-free season (and the corresponding growing season) has been increasing nationally since the 1980s, with the largest increases occurring in the western United States, affecting ecosystems and agriculture. Across the United States, the growing season is projected to continue to lengthen.**

5. **Average U.S. precipitation has increased since 1900, but some areas have had increases greater than the national average, and some areas have had decreases. More winter and spring precipitation is projected for the northern United States, and less for the Southwest, over this century.**

6. **Heavy downpours are increasing nationally, especially over the last three to five decades. Largest increases are in the Midwest and Northeast. Increases in the frequency and intensity of extreme precipitation events are projected for all U.S. regions.**

7. **There have been changes in some types of extreme weather events over the last several decades. Heat waves have become more frequent and intense, especially in the West. Cold waves have become less frequent and intense across the nation. There have been regional trends in floods and droughts. Droughts in the Southwest and heat waves everywhere are projected to become more intense, and cold waves less intense everywhere.**

8. **The intensity, frequency, and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Category 4 and 5) hurricanes, have all increased since the early 1980s. The relative contributions of human and natural causes to these increases are still uncertain. Hurricane-associated storm intensity and rainfall rates are projected to increase as the climate continues to warm.**

9. **Winter storms have increased in frequency and intensity since the 1950s, and their tracks have shifted northward over the United States. Other trends in severe storms, including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds, are uncertain and are being studied intensively.**

Continued

Key Messages (Continued)

10. Global sea level has risen by about 8 inches since reliable record keeping began in 1880. It is projected to rise another 1 to 4 feet by 2100.

11. Rising temperatures are reducing ice volume and surface extent on land, lakes, and sea. This loss of ice is expected to continue. The Arctic Ocean is expected to become essentially ice free in summer before mid-century.

12. The oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually and are becoming more acidic as a result, leading to concerns about intensifying impacts on marine ecosystems.

This chapter summarizes how climate is changing, why it is changing, and what is projected for the future. While the focus is on changes in the United States, the need to provide context sometimes requires a broader geographical perspective. Additional geographic detail is presented in the regional chapters of this report. Further details on the topics covered by this chapter are provided in the Climate Science Supplement and Frequently Asked Questions Appendices.

Since the second National Climate Assessment was published in 2009,[1] the climate has continued to change, with resulting effects on the United States. The trends described in the 2009 report have continued, and our understanding of the data and ability to model the many facets of the climate system have increased substantially. Several noteworthy advances are mentioned in the box below.

The 12 key messages presented above are repeated below, together with supporting evidence for those messages. The discussion of each key message begins with a summary of recent variations or trends, followed by projections of the corresponding changes for the future.

What's new?

- Continued warming and an increased understanding of the U.S. temperature record, as well as multiple other sources of evidence, have strengthened our confidence in the conclusions that the warming trend is clear and primarily the result of human activities. For the contiguous United States, the last decade was the warmest on record, and 2012 was the warmest year on record.
- Heavy precipitation and extreme heat events are increasing in a manner consistent with model projections; the risks of such extreme events will rise in the future.
- The sharp decline in summer Arctic sea ice has continued, is unprecedented, and is consistent with human-induced climate change. A new record for minimum area of Arctic sea ice was set in 2012.
- A longer and better-quality history of sea level rise has increased confidence that recent trends are unusual and human-induced. Limited knowledge of ice sheet dynamics leads to a broad range for projected sea level rise over this century.
- New approaches to building scenarios of the future have allowed for investigations of the implications of larger reductions in heat trapping gas emissions than examined previously.

Reference periods for graphs

Many of the graphs in this report illustrate historical changes and future trends in climate compared to some reference period, with the choice of this period determined by the purpose of the graph and the availability of data. The great majority of graphs are based on one of two reference periods. The period 1901-1960 is used for graphs that illustrate past changes in climate conditions, whether in observations or in model simulations. The choice of 1960 as the ending date of this period was based on past changes in human influences on the climate system. Human-induced forcing exhibited a slow rise during the early part of the last century but then accelerated after 1960.[2] Thus, these graphs highlight observed changes in climate during the period of rapid increase in human-caused forcing and also reveal how well climate models simulate these observed changes. The beginning date of 1901 was chosen because earlier historical observations are less reliable and because many climate model simulations begin in 1900 or 1901. The other commonly used reference period is 1971-2000, which is consistent with the World Meteorological Organization's recommended use of 30-year periods for climate statistics. This is used for graphs that illustrate projected future changes simulated by climate models. The purpose of these graphs is to show projected changes compared to a period that people have recently experienced and can remember; thus, the most recent available 30-year period was chosen (the historical period simulated by the CMIP3 models ends in 1999 or 2000).

Key Message 1: Observed Climate Change

Global climate is changing and this change is apparent across a wide range of observations. The global warming of the past 50 years is primarily due to human activities.

Climate is defined as long-term averages and variations in weather measured over a period of several decades. The Earth's climate system includes the land surface, atmosphere, oceans, and ice. Many aspects of the global climate are changing rapidly, and the primary drivers of that change are human in origin. Evidence for changes in the climate system abounds, from the top of the atmosphere to the depths of the oceans (Figure 2.1).[3] Scientists and engineers from around the world have compiled this evidence using satellites, weather balloons, thermometers at surface stations, and many other types of observing systems that monitor the Earth's weather and climate. The sum total of this evidence tells an unambiguous story: the planet is warming.

Ten Indicators of a Warming World

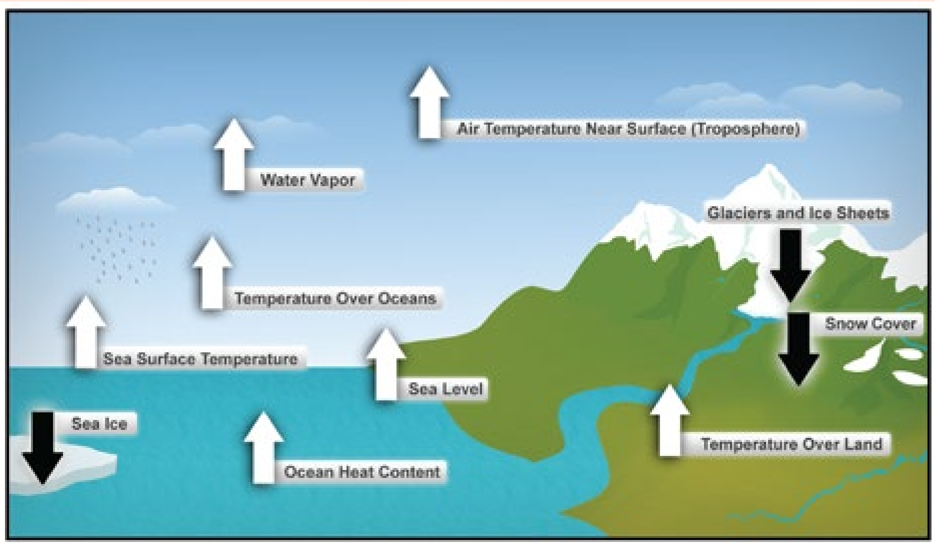

Figure 2.1. These are just some of the indicators measured globally over many decades that show that the Earth's climate is warming. White arrows indicate increasing trends, and black arrows indicate decreasing trends. All the indicators expected to increase in a warming world are, in fact, increasing, and all those expected to decrease in a warming world are decreasing. (Figure source: NOAA NCDC based on data updated from Kennedy et al. 2010[3]).

Temperatures at the surface, in the troposphere (the active weather layer extending up to about 5 to 10 miles above the ground), and in the oceans have all increased over recent decades (Figure 2.2). Consistent with our scientific understanding, the largest increases in temperature are occurring closer to the poles, especially in the Arctic. Snow and ice cover have decreased in most areas. Atmospheric water vapor is increasing in the lower atmosphere, because a warmer atmosphere can hold more water. Sea levels are also increasing (see Key Message 10). Changes in other climate-relevant indicators such as growing season length have been observed in many areas. Worldwide, the observed changes in average conditions have been accompanied by increasing trends in extremes of heat and heavy precipitation events, and decreases in extreme cold.[4]

Natural drivers of climate cannot explain the recent observed warming. Over the last five decades, natural factors (solar forcing and volcanoes) alone would actually have led to a slight cooling (see Figure 2.3).[5]

The majority of the warming at the global scale over the past 50 years can only be explained by the effects of human influences,[5,6,7] especially the emissions from burning fossil fuels (coal, oil, and natural gas) and from deforestation. The emissions from human influences that are affecting climate include heat-trapping gases such as carbon dioxide (CO_2), methane, and nitrous oxide, and particles such as black carbon (soot), which has a warming influence, and sulfates, which have an overall cooling influence (see Appendix 3: Climate Science Supplement for further discussion).[8,9] In addition to human-induced global climate change, local climate can also be affected by other human factors (such as crop irrigation) and natural variability (for example, Ashley et al. 2012; DeAngelis et al. 2010; Degu et al. 2011; Lo and Famiglietti 2013[10]).

The conclusion that human influences are the primary driver of recent climate change is based on multiple lines of independent evidence. The first line of evidence is our fundamental understanding of how certain gases trap heat, how the climate system responds to increases in these gases, and how other human and natural factors influence climate. The second line of evidence is from reconstructions of past climates using evidence such as tree rings, ice cores, and corals. These show that global surface temperatures over the last several decades are clearly unusual, with the last decade (2000-2009) warmer than any time in at least the last 1300 years and perhaps much longer.[11]

Global Temperature and Carbon Dioxide

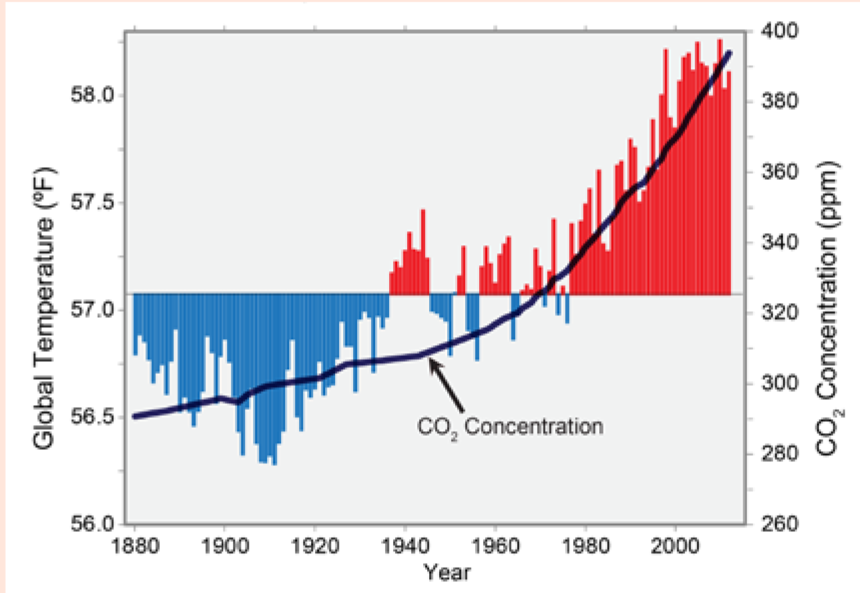

Figure 2.2. Global annual average temperature (as measured over both land and oceans) has increased by more than 1.5°F (0.8°C) since 1880 (through 2012). Red bars show temperatures above the long-term average, and blue bars indicate temperatures below the long-term average. The black line shows atmospheric carbon dioxide (CO_2) concentration in parts per million (ppm). While there is a clear long-term global warming trend, some years do not show a temperature increase relative to the previous year, and some years show greater changes than others. These year-to-year fluctuations in temperature are due to natural processes, such as the effects of El Niños, La Niñas, and volcanic eruptions. (Figure source: updated from Karl et al. 2009[1]).

Separating Human and Natural Influences on Climate

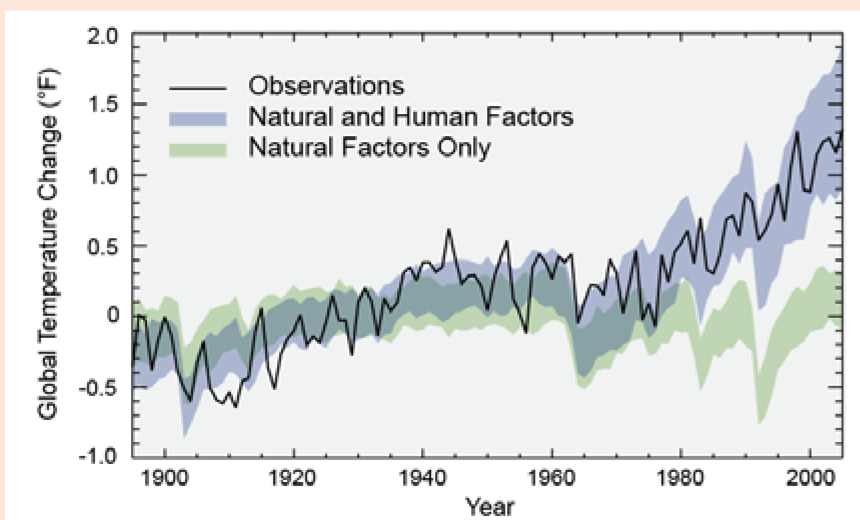

Figure 2.3. Observed global average changes (black line), model simulations using only changes in natural factors (solar and volcanic) in green, and model simulations with the addition of human-induced emissions (blue). Climate changes since 1950 cannot be explained by natural factors or variability, and can only be explained by human factors. (Figure source: adapted from Huber and Knutti[29]).

The third line of evidence comes from using climate models to simulate the climate of the past century, separating the human and natural factors that influence climate. When the human factors are removed, these models show that solar and volcanic activity would have tended to slightly cool the earth, and other natural variations are too small to explain the amount of warming. Only when the human influences are included do the models reproduce the warming observed over the past 50 years (see Figure 2.3).

Another line of evidence involves so-called "fingerprint" studies that are able to attribute observed climate changes to particular causes. For example, the fact that the stratosphere (the layer above the troposphere) is cooling while the Earth's surface and lower atmosphere is warming is a fingerprint that the warming is due to increases in heat-trapping gases. In contrast, if the observed warming had been due to increases in solar output, Earth's atmosphere would have warmed throughout its entire extent, including the stratosphere.[6]

In addition to such temperature analyses, scientific attribution of observed changes to human influence extends to many other aspects of climate, such as changing patterns in precipitation,[12,13] increasing humidity,[14,15] changes in pressure,[16] and increasing ocean heat content.[17] Further discussion of how we know the recent changes in climate are caused by human activity is provided in Appendix 3: Climate Science Supplement.

Natural variations in climate include the effects of cycles such as El Niño, La Niña and other ocean cycles; the 11-year sunspot cycle and other changes in energy from the sun; and the effects of volcanic eruptions. Globally, natural variations can be as large as human-induced climate change over timescales of up to a few decades. However, changes in climate at the global scale observed over the past 50 years are far larger than can be accounted for by natural variability. Changes in climate at the local to regional scale can be influenced by natural variability for multiple decades.[18] This can affect the interpretation of climate trends observed regionally across the U.S. (see Appendix 3: Climate Science Supplement).

Globally averaged surface air temperature has slowed its rate of increase since the late 1990s. This is not in conflict with our basic understanding of global warming and its primary cause. The decade of 2000 to 2009 was still the warmest decade on record. In addition, global surface air temperature does not always increase steadily. This time period is too short to signify a change in the warming trend, as climate trends are measured over periods of decades, not years.[19,20,21,22] Such decade-long slowdowns or even reversals in trend have occurred before in the global instrumental record (for example, 1900-1910 and 1940-1950; see Figure 2.2), including three decade-long periods since 1970, each followed by a sharp temperature rise.[23] Nonetheless, satellite and ocean observations indicate that the Earth-atmosphere climate system has continued to gain heat energy.[24]

There are a number of possible contributions to the lower rate of increase over the last 15 years. First, the solar output during the latest 11-year solar cycle has been lower over the past 15 years than the past 60 years. Second, a series of mildly explosive volcanoes, which increased stratospheric particles, likely had more of a cooling effect than previously recognized.[25] Third, the high incidence of La Niña events in the last 15 years has played a role in the observed trends.[20,26] Recent analyses[27] suggest that more of the increase in heat energy during this period has been transferred to the deep ocean than previously. While this might temporarily slow the rate of increase in surface air temperature, ultimately it will prolong the effects of global warming because the oceans hold heat for longer than the atmosphere does.

Climate models are not intended to match the real-world timing of natural climate variations – instead, models have their own internal timing for such variations. Most modeling studies do not yet account for the observed changes in solar and volcanic forcing mentioned in the previous paragraph. Therefore, it is not surprising that the timing of such a slowdown in the rate of increase in the models would be different than that observed, although it is important to note that such periods *have* been simulated by climate models, with the deep oceans absorbing the extra heat during those decades.[28]

Oil used for transportation and coal used for electricity generation are the largest contributors to the rise in carbon dioxide that is the primary driver of observed changes in climate over recent decades.

Models used in the assessment

This report uses various projections from models of the physical processes affecting the Earth's climate system, which are discussed further in Appendix 3: Climate Science Supplement. Three distinct sets of model simulations for past and projected changes in climate are used:

- Coupled Model Intercomparison Project, 3rd phase (CMIP3): global model analyses done for the Fourth Intergovernmental Panel on Climate Change (IPCC) assessment. Spatial resolutions typically vary from 125 to 187 miles (at mid-latitudes); approximately 25 representations of different models (not all are used in all studies). CMIP3 findings are the foundation for most of the impact analyses included in this assessment.
- Coupled Model Intercomparison Project, 5th phase (CMIP5): newer global model analyses done for the Fifth IPCC assessment generally based on improved formulations of the CMIP3 models. Spatial resolutions typically vary from 62 to 125 miles; about 30 representations of different models (not all are used in all studies); this new information was not available in time to serve as the foundation for the impacts analyses in this assessment, and information from CMIP5 is primarily provided for comparison purposes.
- North American Regional Climate Change Assessment Program (NARCCAP): six regional climate model analyses (and limited time-slice analyses from two global models) for the continental U.S. run at about 30-mile horizontal resolution. The analyses were done for past (1971-2000) and projected (2041-2070) time periods. Coarser resolution results from four of the CMIP3 models were used as the boundary conditions for the NARCCAP regional climate model studies, with each of the regional models doing analyses with boundary conditions from two of the CMIP3 models.

The scenarios for future human-related emissions of the relevant gases and particles used in these models are further discussed in Appendix 3: Climate Science Supplement. The emissions in these scenarios depend on various assumptions about changes in global population, economic and technological development, and choices in transportation and energy use.

Key Message 2: Future Climate Change

Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, and how sensitive the Earth's climate is to those emissions.

A certain amount of continued warming of the planet is projected to occur as a result of human-induced emissions to date; another 0.5°F increase would be expected over the next few decades even if all emissions from human activities suddenly stopped,[30] although natural variability could still play an important role over this time period.[31] However, choices made now and in the next few decades will determine the amount of additional future warming. Beyond mid-century, lower levels of heat-trapping gases in scenarios with reduced emissions will lead to noticeably less future warming. Higher emissions levels will result in more warming, and thus more severe impacts on human society and the natural world.

Confidence in projections of future climate change has increased. The wider range of potential changes in global average temperature in the latest generation of climate model simulations[32] used in the Intergovernmental Panel on Climate Change's (IPCC) current assessment – versus those in the previous assessment[8] – is simply a result of considering more options for future human behavior. For example, one of the scenarios included in the IPCC's latest assessment assumes aggressive emissions reductions designed to limit the global temperature increase to 3.6°F (2°C) above pre-industrial levels.[33] This path would require rapid emissions reductions (more than 70% reduction in human-related emissions by 2050, and net negative emissions by 2100 – see the Appendix 3: Climate Science, Supplemental Message 5) sufficient to achieve heat-trapping gas concentrations well below those of any of the scenarios considered by the IPCC in its 2007 assessment. Such scenarios enable the investigation of climate impacts that would be avoided by deliberate, substantial reductions in heat-trapping gas emissions.

Projections of future changes in precipitation show small increases in the global average but substantial shifts in where and how precipitation falls. Generally, areas closest to the poles are projected to receive more precipitation, while the dry subtropics (the region just outside the tropics, between 23° and 35° on either side of the equator) expand toward the poles and receive less rain. Increases in tropical precipitation are projected during rainy seasons (such as monsoons), especially over the tropical Pacific. Certain regions, including the western U.S. (especially the Southwest[1]) and the Mediterranean, are presently dry and are expected to become drier. The widespread trend of increasing heavy downpours is expected to continue, with precipitation becoming less frequent but more intense.[34] The patterns of the projected changes of precipitation do not contain the spatial details that characterize observed precipitation, especially in mountainous terrain, because the projections are averages from multiple models and because the effective resolution of global climate models is roughly 100-200 miles.

Emissions Levels Determine Temperature Rises

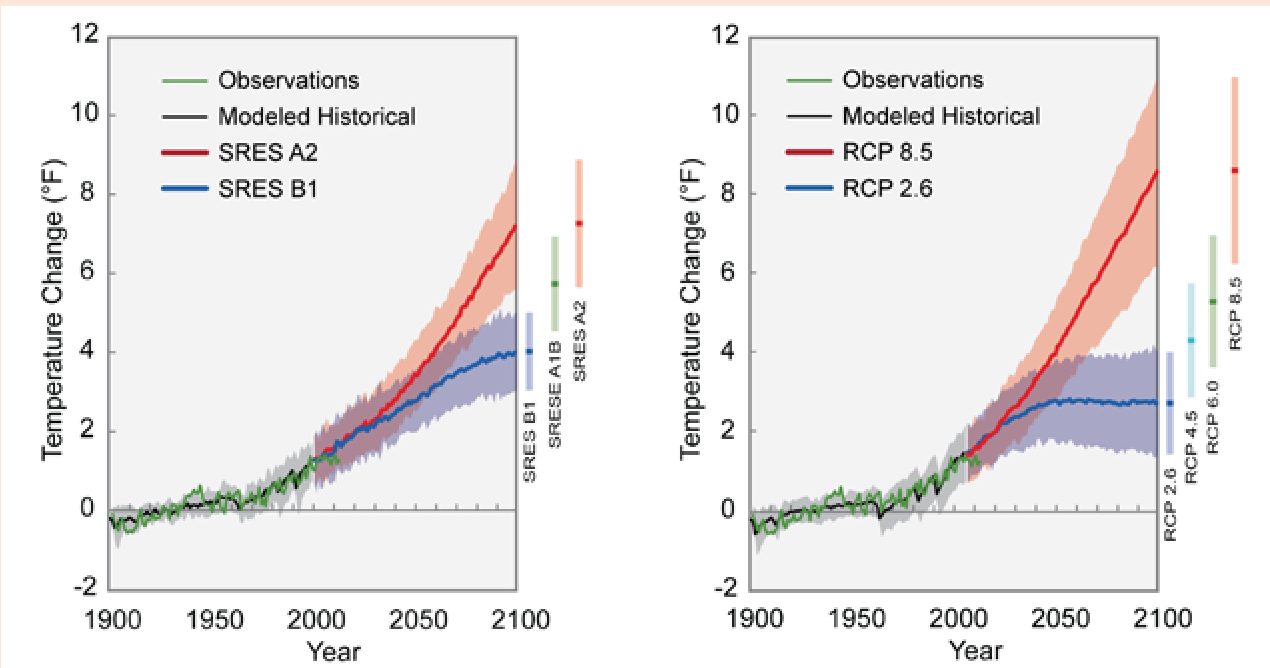

Figure 2.4. Different amounts of heat-trapping gases released into the atmosphere by human activities produce different projected increases in Earth's temperature. In the figure, each line represents a central estimate of global average temperature rise (relative to the 1901-1960 average) for a specific emissions pathway. Shading indicates the range (5th to 95th percentile) of results from a suite of climate models. Projections in 2099 for additional emissions pathways are indicated by the bars to the right of each panel. In all cases, temperatures are expected to rise, although the difference between lower and higher emissions pathways is substantial. **(Left)** The panel shows the two main scenarios (SRES – Special Report on Emissions Scenarios) used in this report: A2 assumes continued increases in emissions throughout this century, and B1 assumes much slower increases in emissions beginning now and significant emissions reductions beginning around 2050, though not due explicitly to climate change policies. **(Right)** The panel shows newer analyses, which are results from the most recent generation of climate models (CMIP5) using the most recent emissions pathways (RCPs – Representative Concentration Pathways). Some of these new projections explicitly consider climate policies that would result in emissions reductions, which the SRES set did not.[35] The newest set includes both lower and higher pathways than did the previous set. The lowest emissions pathway shown here, RCP 2.6, assumes immediate and rapid reductions in emissions and would result in about 2.5°F of warming in this century. The highest pathway, RCP 8.5, roughly similar to a continuation of the current path of global emissions increases, is projected to lead to more than 8°F warming by 2100, with a high-end possibility of more than 11°F. (Data from CMIP3, CMIP5, and NOAA NCDC).

Projected Change in Average Annual Temperature

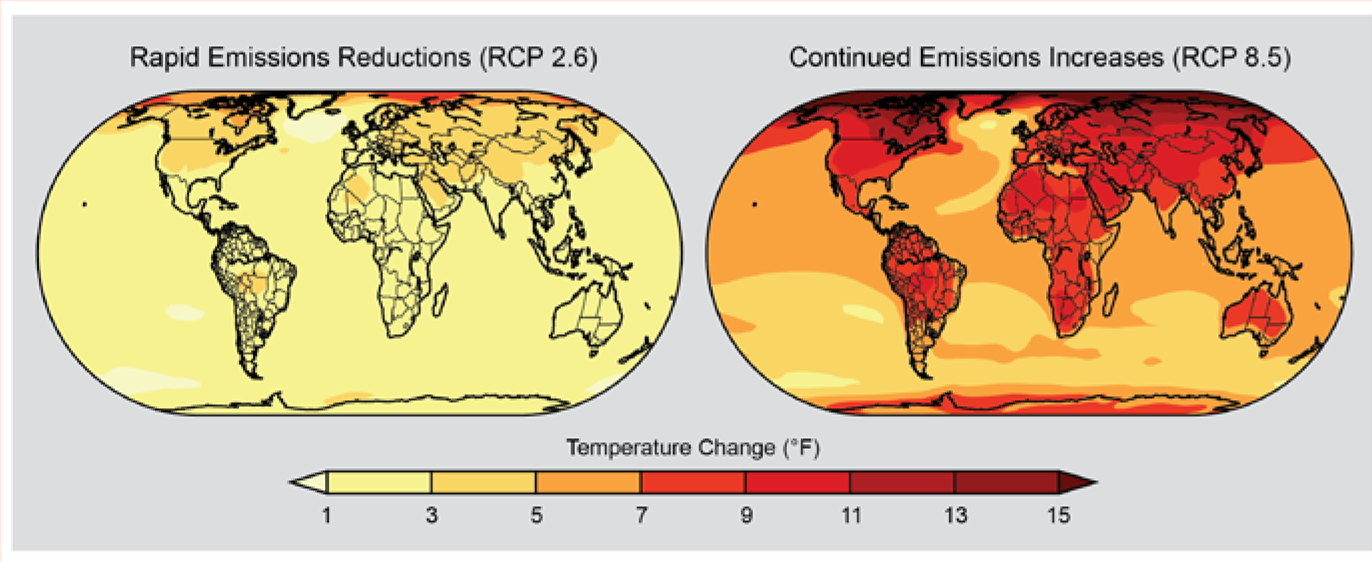

Figure 2.5. Projected change in average annual temperature over the period 2071-2099 (compared to the period 1970-1999) under a low scenario that assumes rapid reductions in emissions and concentrations of heat-trapping gases (RCP 2.6), and a higher scenario that assumes continued increases in emissions (RCP 8.5). (Figure source: NOAA NCDC / CICS-NC).

Projected Change in Average Annual Precipitation

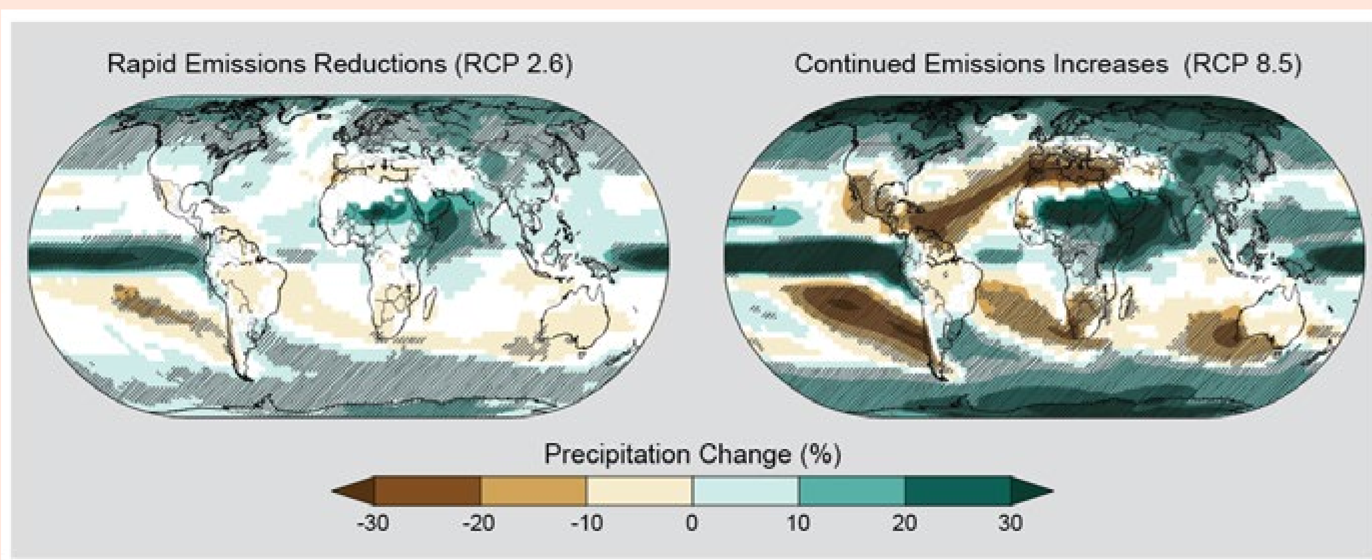

Figure 2.6. Projected change in average annual precipitation over the period 2071-2099 (compared to the period 1970-1999) under a low scenario that assumes rapid reductions in emissions and concentrations of heat-trapping gasses (RCP 2.6), and a higher scenario that assumes continued increases in emissions (RCP 8.5). Hatched areas indicate confidence that the projected changes are significant and consistent among models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. In general, northern parts of the U.S. (especially the Northeast and Alaska) are projected to receive more precipitation, while southern parts (especially the Southwest) are projected to receive less. (Figure source: NOAA NCDC / CICS-NC).

Climate sensitivity

"Climate sensitivity" is an important concept because it helps us estimate how much warming might be expected for a given increase in the amount of heat-trapping gases. It is defined as the amount of warming expected if carbon dioxide (CO_2) concentrations doubled from pre-industrial levels and then remained constant until Earth's temperature reached a new equilibrium over timescales of centuries to millennia. Climate sensitivity accounts for feedbacks in the climate system that can either dampen or amplify warming. The feedbacks primarily determining that response are related to water vapor, ice and snow reflectivity, and clouds.[8] Cloud feedbacks have the largest uncertainty. The net effect of these feedbacks is expected to amplify warming.[8]

Climate sensitivity has long been estimated to be in the range of 2.7°F to 8.1°F. As discussed in Appendix 3: Climate Science Supplement, recent evidence lends further confidence in this range.

One important determinant of how much climate will change is the effect of so-called "feedbacks" in the climate system, which can either dampen or amplify the initial effect of human influences on temperature. One important climate feedback is the loss of summer Arctic sea ice, allowing absorption of substantially more of the sun's heat in the Arctic, increasing warming, and possibly causing changes in weather patterns over the United States.

The observed drastic reduction in sea ice can also lead to a "tipping point" – a point beyond which an abrupt or irreversible transition to a different climatic state occurs. In this case, the dramatic loss of sea ice could tip the Arctic Ocean into a permanent, nearly ice-free state in summer, with repercussions that may extend far beyond the Arctic. Such potential "tipping points" have been identified in various components of the Earth's climate system and could have important effects on future climate. The extent and magnitude of these potential effects are still unknown. These are discussed further in the Appendix 4: Frequently Asked Questions, under Question T.

Key Message 3: Recent U.S. Temperature Trends

U.S. average temperature has increased by 1.3°F to 1.9°F since record keeping began in 1895; most of this increase has occurred since about 1970. The most recent decade was the nation's warmest on record. Temperatures in the United States are expected to continue to rise. Because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, uniform or smooth across the country or over time.

There have been substantial advances in our understanding of the U.S. temperature record since the 2009 assessment (see Appendix 3: Climate Science, Supplemental Message 7 for more information). These advances confirm that the U.S. annually averaged temperature has increased by 1.3°F to 1.9°F since 1895.[1,36,37,38] However, this increase was not constant over time. In particular, temperatures generally rose until about 1940, declined slightly until about 1970, then increased rapidly thereafter. The year 2012 was the warmest on record for the contiguous United States. Over shorter time scales (one to two decades), natural variability can reduce the rate of warming or even create a temporary cooling (see Appendix 3: Climate Science, Supplemental Message 3). The cooling in mid-century that was especially prevalent over the eastern half of the U.S. may have stemmed partly from such natural variations and partly from human influences, in particular the cooling effects of sulfate particles from coal-burning power plants,[39] before these sulfur emissions were regulated to address health and acid rain concerns.

Quantifying U.S. temperature rise

Quantifying long-term increases of temperature in the U.S. in a single number is challenging because the increase has not been constant over time. The increase can be quantified in a number of ways, but all of them show significant warming over the U.S. since the instrumental record began in 1895. For example, fitting a linear trend over the period 1895 to 2012 yields an increase in the range of 1.3 to 1.9°F. Another approach, comparing the average temperature during the first decade of record with the average during the last decade of record, yields a 1.9°F increase. A third approach, calculating the difference between the 1901-1960 average and the past decade average yields a change of 1.5°F. Thus, the temperature increase cited in this assessment is described as 1.3°F to 1.9°F since 1895. Notably, however, the rate of rise in temperature over the past 4 to 5 decades has been greater than the rate over earlier decades.

Observed U.S. Temperature Change

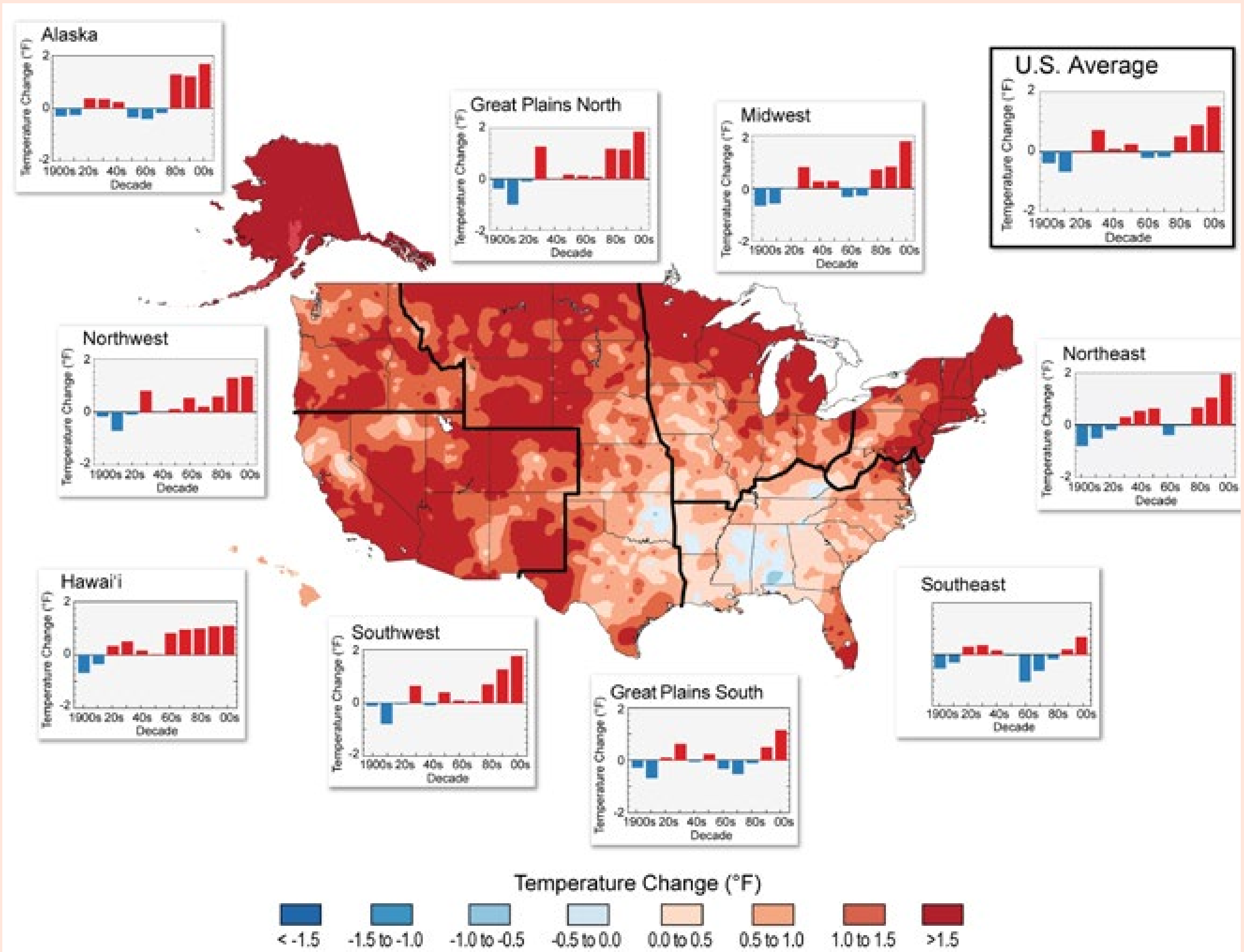

Figure 2.7. The colors on the map show temperature changes over the past 22 years (1991-2012) compared to the 1901-1960 average, and compared to the 1951-1980 average for Alaska and Hawai'i. The bars on the graphs show the average temperature changes by decade for 1901-2012 (relative to the 1901-1960 average) for each region. The far right bar in each graph (2000s decade) includes 2011 and 2012. The period from 2001 to 2012 was warmer than any previous decade in every region. (Figure source: NOAA NCDC / CICS-NC).

Since 1991, temperatures have averaged 1°F to 1.5°F higher than 1901-1960 over most of the United States, except for the Southeast, where the warming has been less than 1°F. On a seasonal basis, long-term warming has been greatest in winter and spring.

Warming is ultimately projected for all parts of the nation during this century. In the next few decades, this warming will be roughly 2°F to 4°F in most areas. By the end of the century, U.S. warming is projected to correspond closely to the level of global emissions: roughly 3°F to 5°F under lower emissions scenarios (B1 or RCP 4.5) involving substantial reductions in emissions, and 5°F to 10°F for higher emissions scenarios (A2 or RCP 8.5) that assume continued increases in emissions; the largest temperature increases are projected for the upper Midwest and Alaska.

Future human-induced warming depends on both past and future emissions of heat-trapping gases and changes in the amount of particle pollution. The amount of climate change (aside from natural variability) expected for the next two to three decades is a combination of the warming already built into the climate system by the past history of human emissions of heat-trapping gases, and the expected ongoing increases in emissions of those gases. However, the magnitude of temperature increases over the second half of this century, both in the U.S. and globally, will be primarily determined by the emissions produced now and over the next few decades, and there are substantial differences between higher, fossil-fuel intensive scenarios compared to scenarios in which emissions are reduced. The most recent model projections of climate change due to human activities expand the range of future scenarios considered (particularly at the lower end), but are entirely consistent with the older model results. This consistency increases our confidence in the projections.

Projected Temperature Change

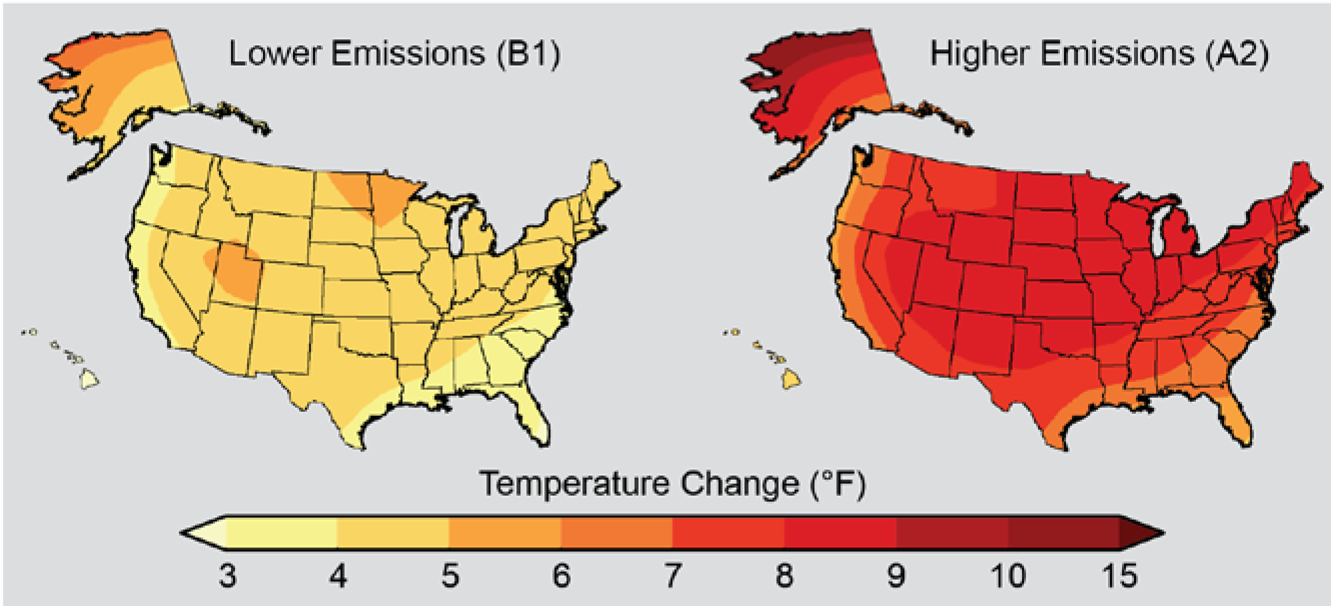

Figure 2.8. Maps show projected change in average surface air temperature in the later part of this century (2071-2099) relative to the later part of the last century (1970-1999) under a scenario that assumes substantial reductions in heat trapping gases (B1, left) and a higher emissions scenario that assumes continued increases in global emissions (A2, right). (See Appendix 3: Climate Science, Supplemental Message 5 for a discussion of temperature changes under a wider range of future scenarios for various periods of this century). (Figure source: NOAA NCDC / CICS-NC).

Newer simulations for projected temperature (CMIP5 models)

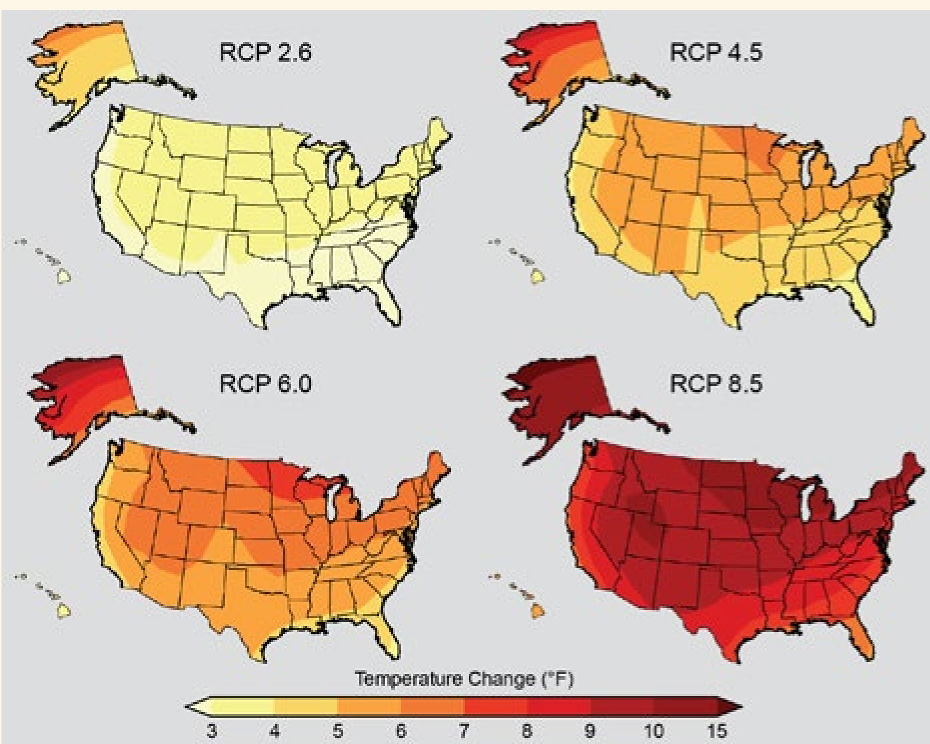

Figure 2.9. The largest uncertainty in projecting climate change beyond the next few decades is the level of heat-trapping gas emissions. The most recent model projections (CMIP5) take into account a wider range of options with regard to human behavior, including a lower scenario than has been considered before (RCP 2.6). This scenario assumes rapid reductions in emissions – more than 70% cuts from current levels by 2050 and further large decreases by 2100 – and the corresponding smaller amount of warming. On the higher end, the scenarios include one that assumes continued increases in emissions (RCP 8.5) and the corresponding greater amount of warming. Also shown are temperature changes for the intermediate scenarios RCP 4.5 (which is most similar to B1) and RCP 6.0 (which is most similar to A1B; see Appendix 3: Climate Science Supplement). Projections show change in average temperature in the later part of this century (2071-2099) relative to the late part of last century (1970-1999). (Figure source: NOAA NCDC / CICS-NC).

Key Message 4: Lengthening Frost-free Season

The length of the frost-free season (and the corresponding growing season) has been increasing nationally since the 1980s, with the largest increases occurring in the western United States, affecting ecosystems and agriculture. Across the United States, the growing season is projected to continue to lengthen.

The length of the frost-free season (and the corresponding growing season) is a major determinant of the types of plants and crops that do well in a particular region. The frost-free season length has been gradually increasing since the 1980s.[40] The last occurrence of 32°F in the spring has been occurring earlier in the year, and the first occurrence of 32°F in the fall has been happening later. During 1991-2011, the average frost-free season was about 10 days longer than during 1901-1960. These observed climate changes have been mirrored by changes in the biosphere, including increases in forest productivity[41,42] and satellite-derived estimates of the length of the growing season.[43] A longer growing season provides a longer period for plant growth and productivity and can slow the increase in atmospheric CO_2 concentrations through increased CO_2 uptake by living things and their environment.[44] The longer growing season can increase the growth of beneficial plants (such as crops and forests) as well as undesirable ones (such as ragweed).[45] In some cases where moisture is limited, the greater evaporation and loss of moisture through plant transpiration (release of water from plant leaves) associated with a longer growing season can mean less productivity because of increased drying[46] and earlier and longer fire seasons.

Observed Increase in Frost-Free Season Length

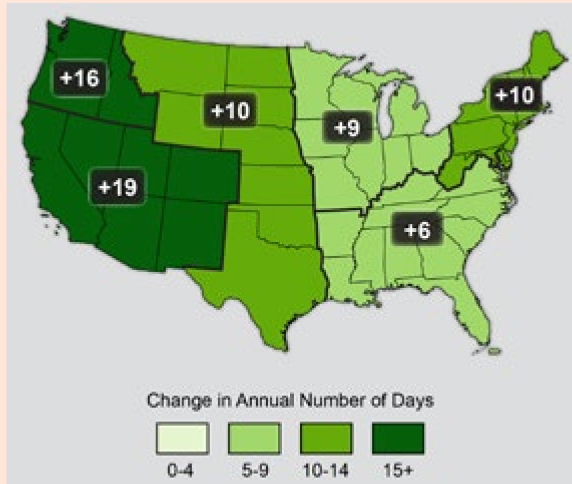

Figure 2.10. The frost-free season length, defined as the period between the last occurrence of 32°F in the spring and the first occurrence of 32°F in the fall, has increased in each U.S. region during 1991-2012 relative to 1901-1960. Increases in frost-free season length correspond to similar increases in growing season length. (Figure source: NOAA NCDC / CICS-NC).

The lengthening of the frost-free season has been somewhat greater in the western U.S. than the eastern United States,[1] increasing by 2 to 3 weeks in the Northwest and Southwest, 1 to 2 weeks in the Midwest, Great Plains, and Northeast, and slightly less than 1 week in the Southeast. These differences mirror the overall trend of more warming in the north and west and less warming in the Southeast.

Projected Changes in Frost-Free Season Length

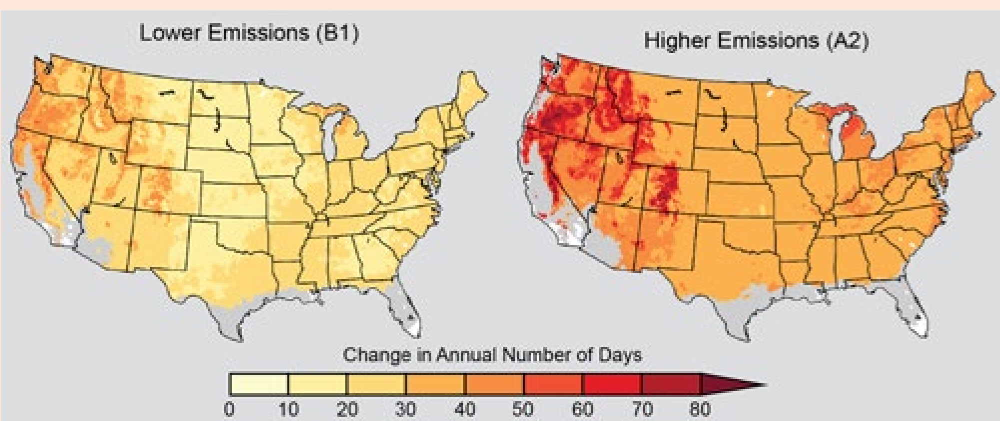

Figure 2.11. The maps show projected increases in frost-free season length for the last three decades of this century (2070-2099 as compared to 1971-2000) under two emissions scenarios, one in which heat-trapping gas emissions continue to grow (A2) and one in which emissions peak in 2050 (B1). Increases in the frost-free season correspond to similar increases in the growing season. White areas are projected to experience no freezes for 2070-2099, and gray areas are projected to experience more than 10 frost-free years during the same period. (Figure source: NOAA NCDC / CICS-NC).

In a future in which heat-trapping gas emissions continue to grow, increases of a month or more in the lengths of the frost-free and growing seasons are projected across most of the U.S. by the end of the century, with slightly smaller increases in the northern Great Plains. The largest increases in the frost-free season (more than 8 weeks) are projected for the western U.S., particularly in high elevation and coastal areas. The increases will be considerably smaller if heat-trapping gas emissions are reduced, although still substantial. These increases are projected to be much greater than the normal year-to-year variability experienced today. The projected changes also imply that the southern boundary of the seasonal freeze zone will move northward, with increasing frequencies of years without subfreezing temperatures in the most southern parts of the United States.

Key Message 5: U.S. Precipitation Change

Average U.S. precipitation has increased since 1900, but some areas have had increases greater than the national average, and some areas have had decreases. More winter and spring precipitation is projected for the northern United States, and less for the Southwest, over this century.

Since 1900, average annual precipitation over the U.S. has increased by roughly 5%. This increase reflects, in part, the major droughts of the 1930s and 1950s, which made the early half of the record drier. There are important regional differences. For instance, precipitation since 1991 (relative to 1901-1960) increased the most in the Northeast (8%), Midwest (9%), and southern Great Plains (8%), while much of the Southeast and Southwest had a mix of areas of increases and decreases.[47,48]

While significant trends in average precipitation have been detected, the fraction of these trends attributable to human activity is difficult to quantify at regional scales because the range of natural variability in precipitation is large. Projected changes are generally small for central portions of the United States. However, if emissions of heat-trapping gases continue their upward trend, certain global patterns of precipitation change are projected to emerge that will affect northern and

Observed U.S. Precipitation Change

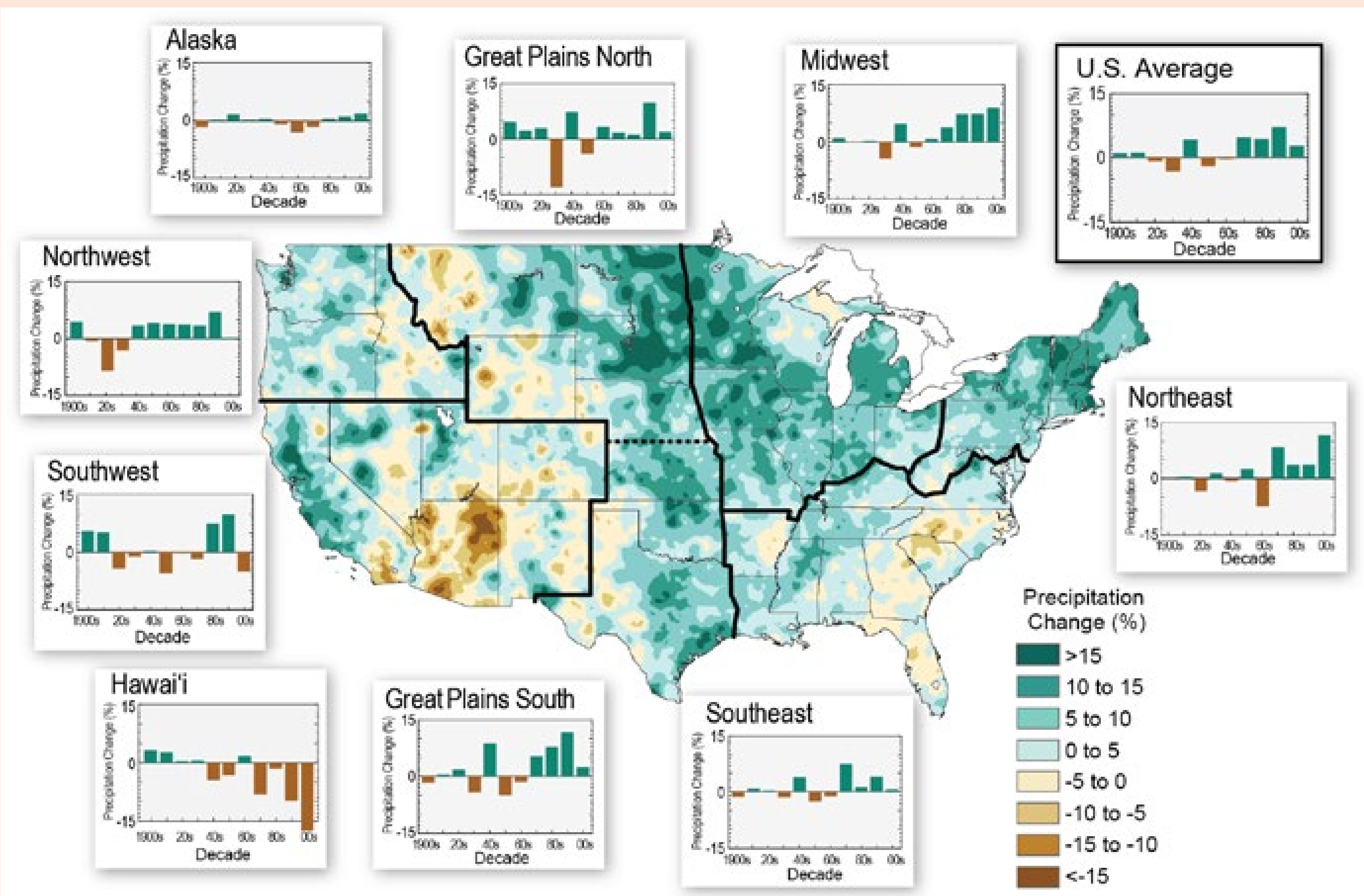

Figure 2.12. The colors on the map show annual total precipitation changes for 1991-2012 compared to the 1901-1960 average, and show wetter conditions in most areas. The bars on the graphs show average precipitation differences by decade for 1901-2012 (relative to the 1901-1960 average) for each region. The far right bar in each graph is for 2001-2012. (Figure source: adapted from Peterson et al. 2013[48]).

southwestern areas of the United States. The northern U.S. is projected to experience more precipitation in the winter and spring (except for the Northwest in the spring), while the Southwest is projected to experience less, particularly in the spring. The contrast between wet and dry areas will increase both in the U.S. and globally – in other words, the wet areas will get wetter and the dry areas will get drier. As discussed in the next section, there has been an increase in the amount of precipitation falling in heavy events[49] and this is projected to continue.

The projected changes in the northern U.S. are a consequence of both a warmer atmosphere (which can hold more moisture than a colder one) and associated changes in large-scale

Uncertainties in Regional Projections

On the global scale, climate model simulations show consistent projections of future conditions under a range of emissions scenarios. For temperature, all models show warming by late this century that is much larger than historical variations nearly everywhere. For precipitation, models are in complete agreement in showing decreases in precipitation in the subtropics and increases in precipitation at higher latitudes.

Models unequivocally project large and historically unprecedented future warming in every region of the U.S. under all of the scenarios used in this assessment. The amount of warming varies substantially between higher versus lower scenarios, and moderately from model to model, but the amount of projected warming is larger than the model-to-model range.

The contiguous U.S. straddles the transition zone between drier conditions in the sub-tropics (south) and wetter conditions at higher latitudes (north). Because the precise location of this zone varies somewhat among models, projected changes in precipitation in central areas of the U.S. range from small increases to small decreases. A clear direction of change only occurs in Alaska and the far north of the contiguous U.S. where increases are projected and in the far Southwest where decreases are projected.

Although this means that changes in overall precipitation are uncertain in many U.S. areas, there is a high degree of certainty that the heaviest precipitation events will increase everywhere, and by large amounts (Figure 2.13). This consistent model projection is well understood and is a direct outcome of the increase in atmospheric moisture caused by warming. There is also more certainty regarding dry spells. The annual maximum number of consecutive dry days is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States. Thus, both extreme wetness and extreme dryness are projected to increase in many areas.

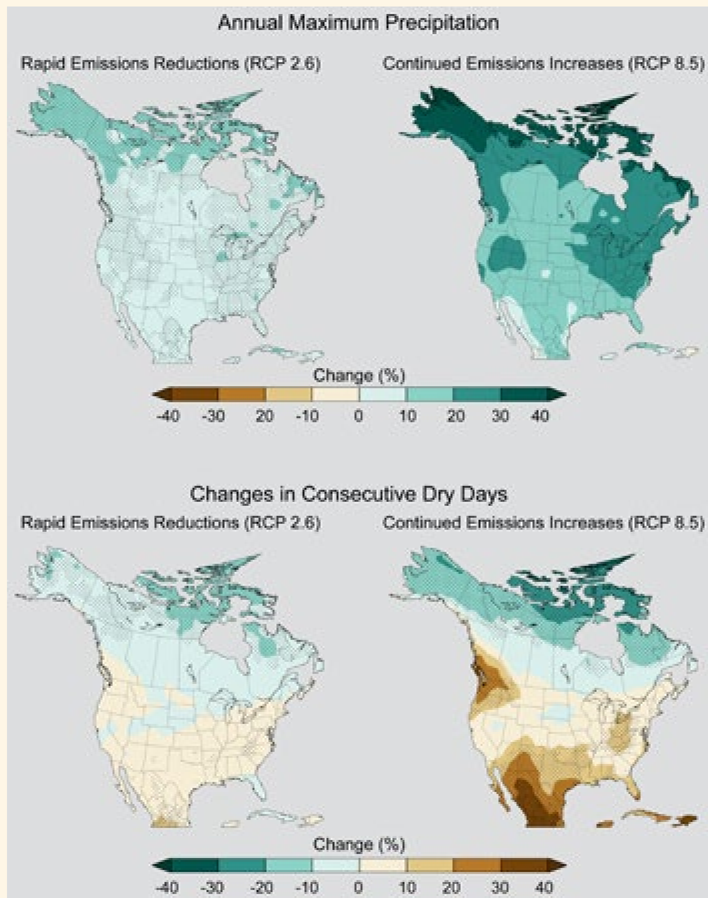

Figure 2.13. Top panels show simulated changes in the average amount of precipitation falling on the wettest day of the year for the period 2070-2099 as compared to 1971-2000 under a scenario that assumes rapid reductions in emissions (RCP 2.6) and one that assumes continued emissions increases (RCP 8.5). Bottom panels show simulated changes in the annual maximum number of consecutive dry days (days receiving less than 0.04 inches (1 mm) of precipitation) under the same two scenarios. Simulations are from CMIP5 models. Stippling indicates areas where changes are consistent among at least 80% of the models used in this analysis. (Figure source: NOAA NCDC / CICS-NC).

Modeling methods that downscale (generate higher spatial resolution) climate projections from coarser global model output can reduce the range of projections to the extent that they incorporate better representation of certain physical processes (such as the influence of topography and convection). However, a sizeable portion of the range is a result of the variations in large-scale patterns produced by the global models and so downscaling methods do not change this.

weather patterns (which affect where precipitation occurs). The projected reduction in Southwest precipitation is a result of changes in large-scale weather patterns, including the northward expansion of the belt of high pressure in the subtropics, which suppresses rainfall. Recent improvements in understanding these mechanisms of change increase confidence in these projections.[50] The patterns of the projected changes of precipitation resulting from human alterations of the climate are geographically smoother in these maps than what will actually be observed because: 1) the precise locations of natural increases and decreases differ from model to model, and averaging across models smooths these differences; and 2) the resolution of current climate models is too coarse to capture fine topographic details, especially in mountainous terrain. Hence, there is considerably more confidence in the large-scale patterns of change than in local details.

In general, a comparison of the various sources of climate model data used in this assessment provides a consistent picture of the large-scale projected precipitation changes

Projected Precipitation Change by Season

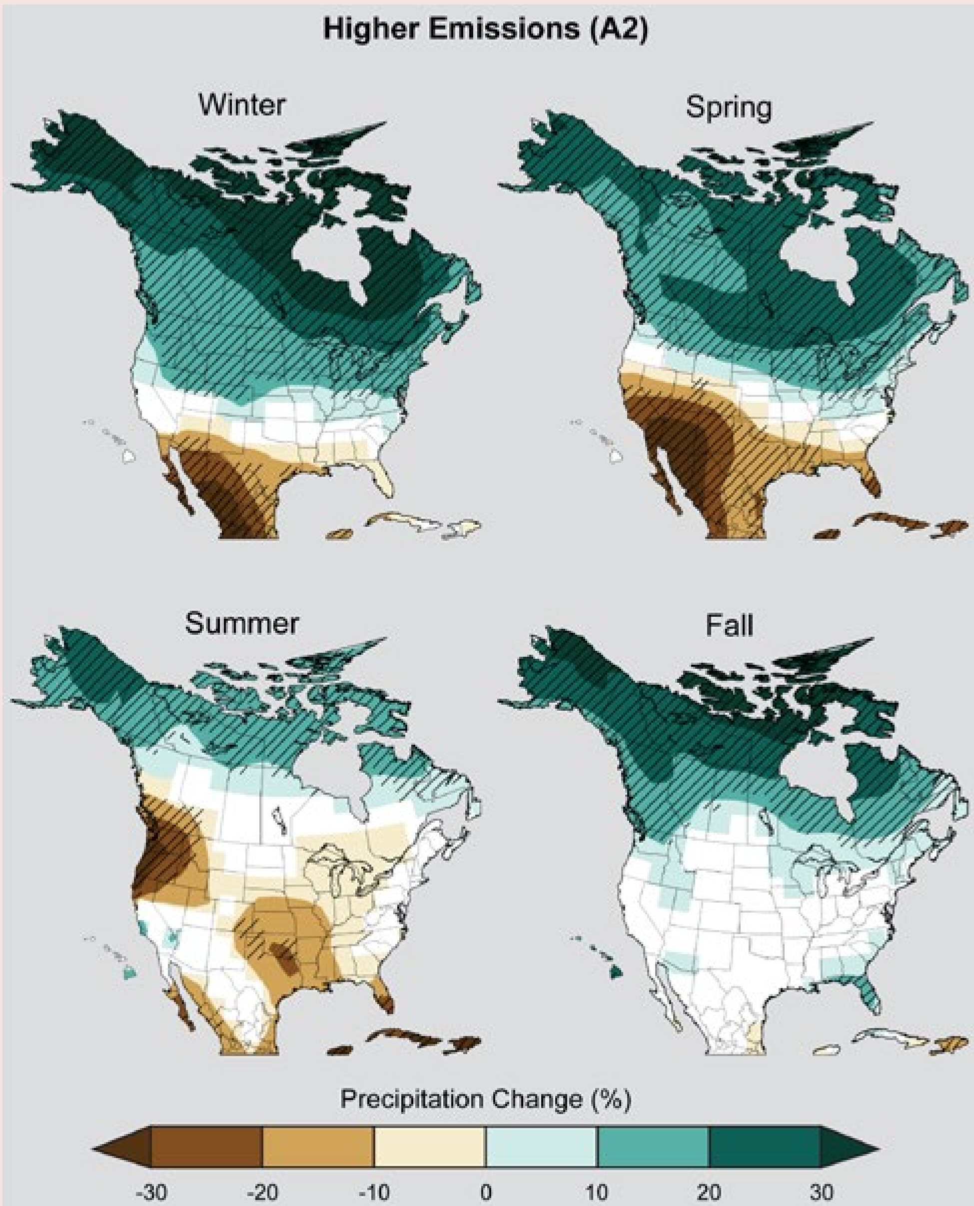

Figure 2.14. Projected change in seasonal precipitation for 2071-2099 (compared to 1970-1999) under an emissions scenario that assumes continued increases in emissions (A2). Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. In general, the northern part of the U.S. is projected to see more winter and spring precipitation, while the southwestern U.S. is projected to experience less precipitation in the spring. (Figure source: NOAA NCDC / CICS-NC).

across the United States (see "Models Used in the Assessment"). Multi-model average changes in all three of these sources show a general pattern of wetter future conditions in the north and drier conditions in the south. The regional suite generally shows conditions that are somewhat wetter overall in the wet areas and not as dry in the dry areas. The general pattern agreement among these three sources, with the wide variations in their spatial resolution, provides confidence that this pattern is robust and not sensitive to the limited spatial resolution of the models. The slightly different conditions in the North American NARCCAP regional analyses for the U.S. appear to arise partially or wholly from the choice of the four CMIP3 global climate models used to drive the regional simulations. These four global models, averaged together, project average changes that are 2% wetter than the average of the suite of global models used in CMIP3.

The patterns of precipitation change in the newer CMIP5 simulations are essentially the same as in the earlier CMIP3 and NARCCAP simulations used in impact analyses throughout this report, increasing confidence in our scientific understanding. The subtle differences between these two sets of projections are mostly due to the wider range of future scenarios considered in the more recent simulations. Thus, the overall picture remains the same: wetter conditions in the north and drier conditions in the Southwest in winter and spring. Drier conditions are projected for summer in most areas of the contiguous U.S. but, outside of the Northwest and south-central region, there is generally not high confidence that the changes will be large compared to natural variability. In all models and scenarios, a transition zone between drier (to the south) and wetter (to the north) shifts northward from the southern U.S. in winter to southern Canada in summer. Wetter conditions are projected for Alaska and northern Canada in all seasons.

Newer simulations for projected precipitation change (CMIP5 models)

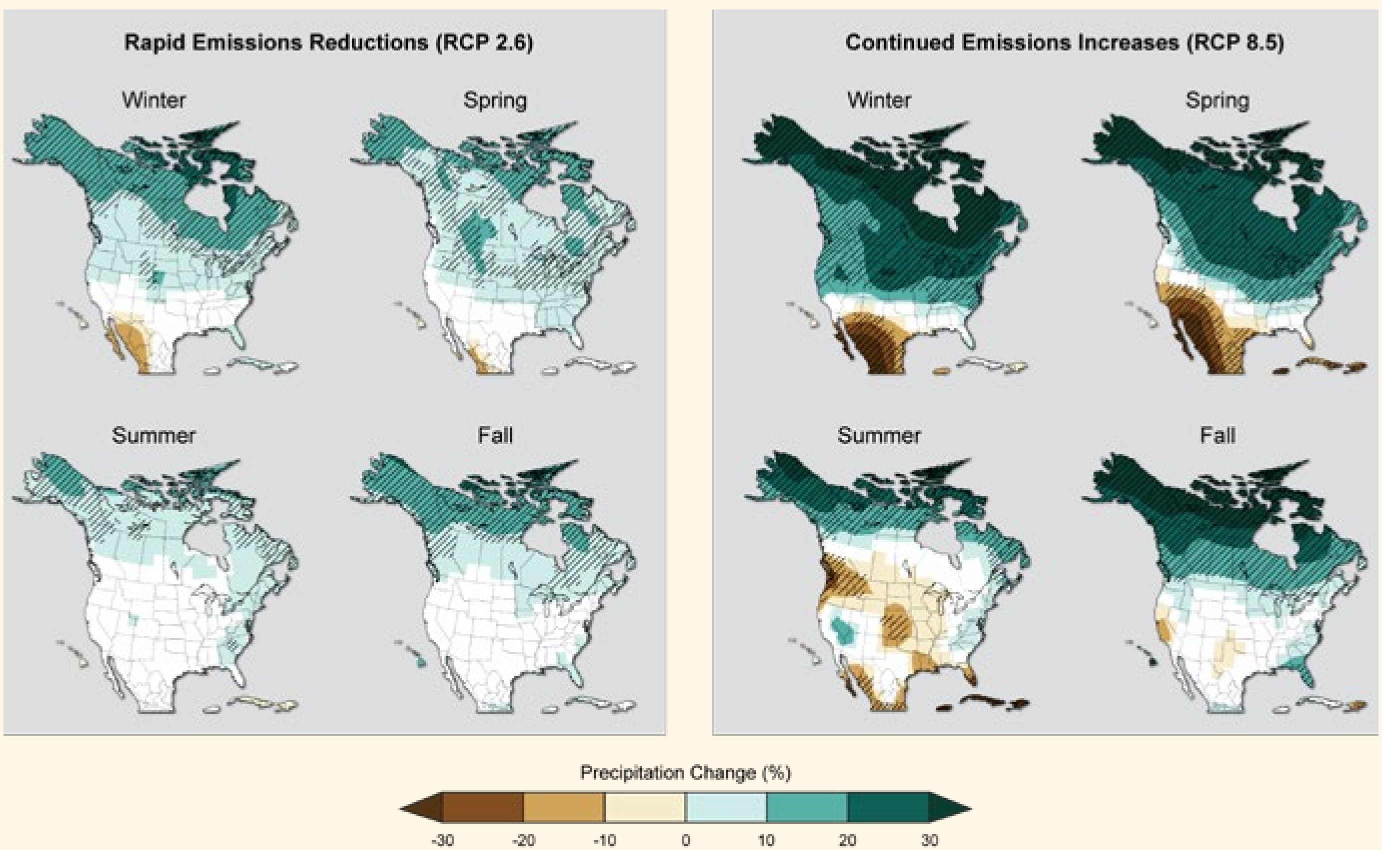

Figure 2.15. Seasonal precipitation change for 2071-2099 (compared to 1970-1999) as projected by recent simulations that include a wider range of scenarios. The maps on the left (RCP 2.6) assume rapid reductions in emissions – more than 70% cuts from current levels by 2050 – and a corresponding much smaller amount of warming and far less precipitation change. On the right, RCP 8.5 assumes continued increases in emissions, with associated large increases in warming and major precipitation changes. These would include, for example, large reductions in spring precipitation in the Southwest and large increases in the Northeast and Midwest. Rapid emissions reductions would be required for the more modest changes in the maps on the left. Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. (Figure source: NOAA NCDC / CICS-NC).

Key Message 6: Heavy Downpours Increasing

Heavy downpours are increasing nationally, especially over the last three to five decades. Largest increases are in the Midwest and Northeast. Increases in the frequency and intensity of extreme precipitation events are projected for all U.S. regions.

Across most of the United States, the heaviest rainfall events have become heavier and more frequent. The amount of rain falling on the heaviest rain days has also increased over the past few decades. Since 1991, the amount of rain falling in very heavy precipitation events has been significantly above average. This increase has been greatest in the Northeast, Midwest, and upper Great Plains – more than 30% above the 1901-1960 average (see Figure 2.18). There has also been an increase in flooding events in the Midwest and Northeast where the largest increases in heavy rain amounts have occurred.

Observed U.S. Trend in Heavy Precipitation

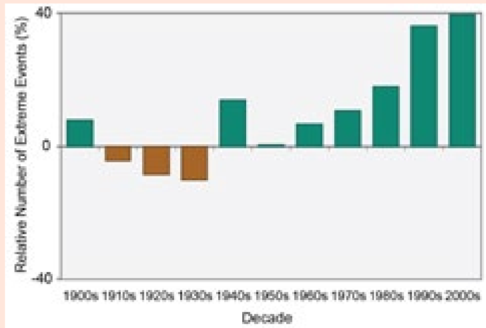

Figure 2.16: One measure of a heavy precipitation event is a 2-day precipitation total that is exceeded on average only once in a five-year period, also known as a once-in-five-year event. As this extreme precipitation index for 1901-2012 shows, the occurrence of such events has become much more common in recent decades. Changes are compared to the period 1901-1960, and do not include Alaska or Hawai'i. The 2000s decade (far right bar) includes 2001-2012. (Figure source: adapted from Kunkel et al. 2013[52]).

Observed Change in Very Heavy Precipitation

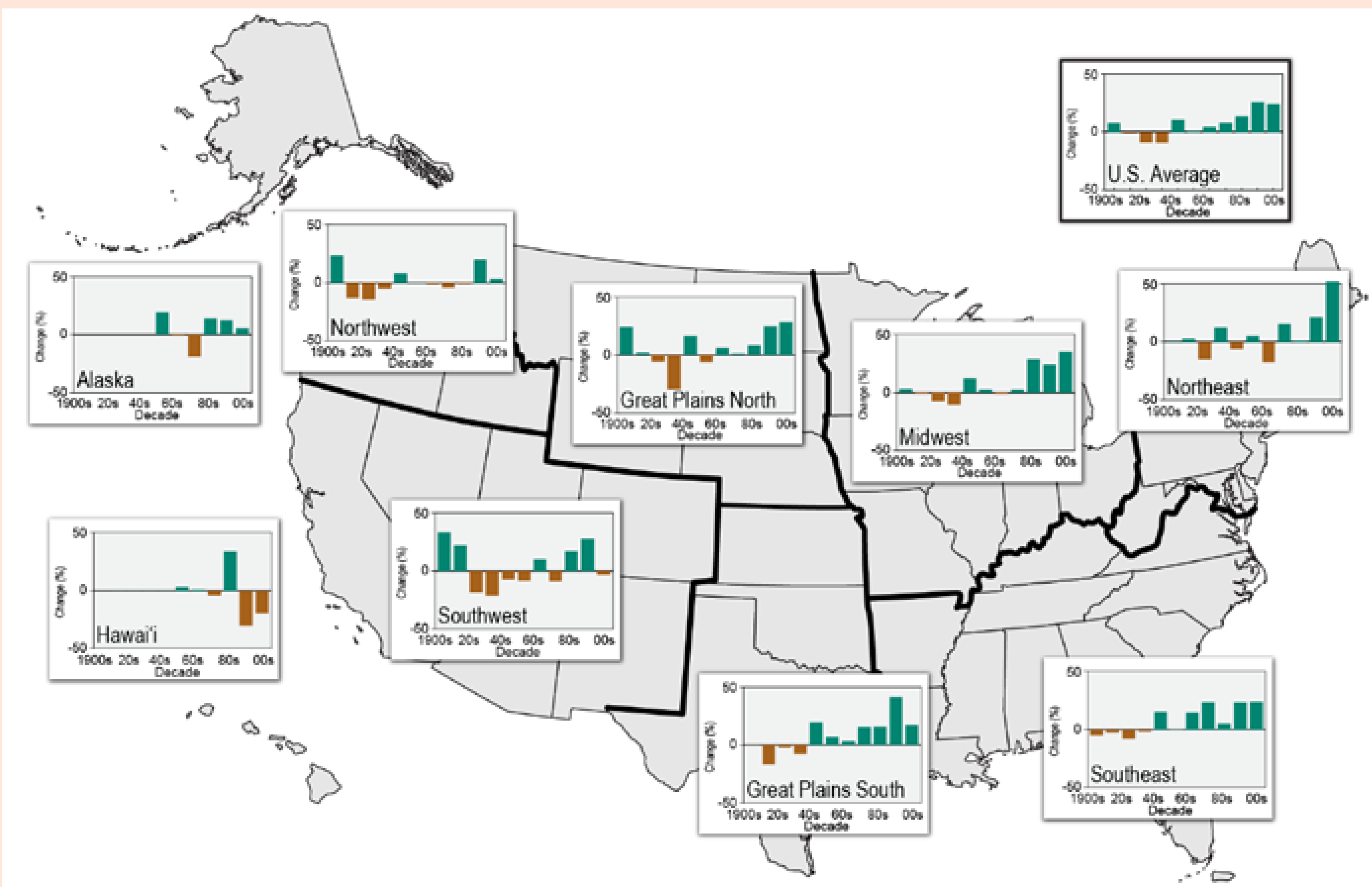

Figure 2.17. Percent changes in the annual amount of precipitation falling in very heavy events, defined as the heaviest 1% of all daily events from 1901 to 2012 for each region. The far right bar is for 2001-2012. In recent decades there have been increases nationally, with the largest increases in the Northeast, Great Plains, Midwest, and Southeast. Changes are compared to the 1901-1960 average for all regions except Alaska and Hawai'i, which are relative to the 1951-1980 average. (Figure source: NOAA NCDC / CICS-NC).

Warmer air can contain more water vapor than cooler air. Global analyses show that the amount of water vapor in the atmosphere has in fact increased over both land and oceans.[14,51] Climate change also alters dynamical characteristics of the atmosphere that in turn affect weather patterns and storms. In the mid-latitudes, where most of the continental U.S. is located, there is an upward trend in extreme precipitation in the vicinity of fronts associated with mid-latitude storms.[52] Locally, natural variations can also be important.[53]

Projections of future climate over the U.S. suggest that the recent trend towards increased heavy precipitation events will continue. This is projected to occur even in regions where total precipitation is projected to decrease, such as the Southwest.[52,54,55]

Observed Change in Very Heavy Precipitation

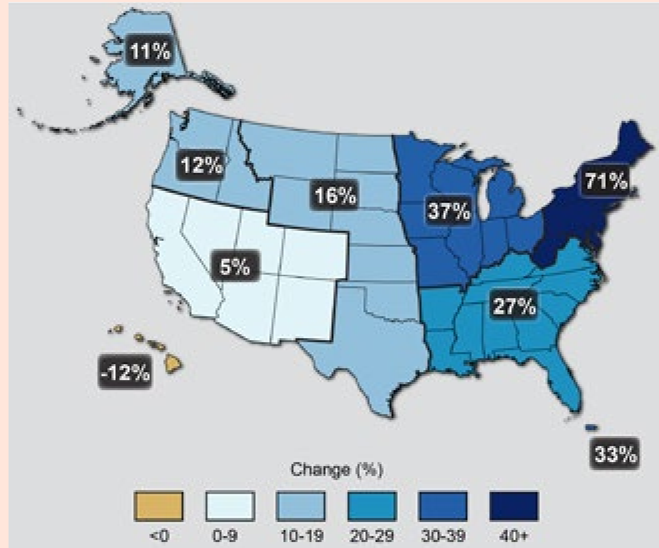

Figure 2.18. The map shows percent increases in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) from 1958 to 2012 for each region of the continental United States. These trends are larger than natural variations for the Northeast, Midwest, Puerto Rico, Southeast, Great Plains, and Alaska. The trends are not larger than natural variations for the Southwest, Hawai'i, and the Northwest. The changes shown in this figure are calculated from the beginning and end points of the trends for 1958 to 2012. (Figure source: updated from Karl et al. 2009[1]).

Projected Change in Heavy Precipitation Events

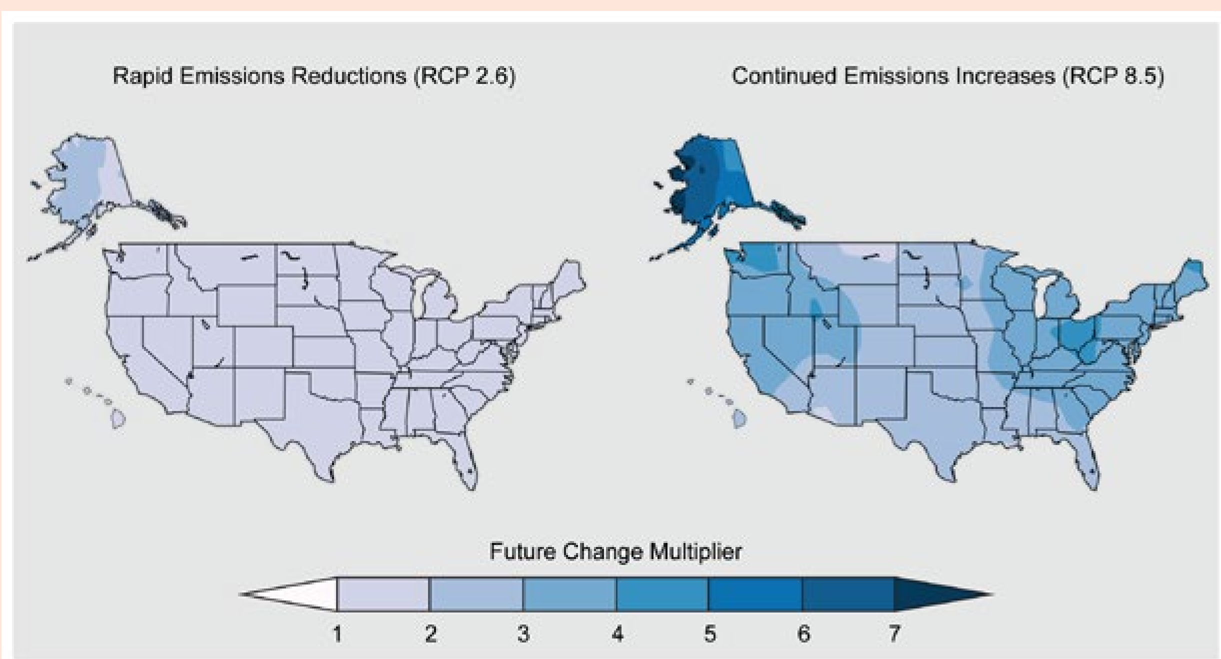

Figure 2.19. Maps show the increase in frequency of extreme daily precipitation events (a daily amount that now occurs once in 20 years) by the later part of this century (2081-2100) compared to the later part of last century (1981-2000). Such extreme events are projected to occur more frequently everywhere in the United States. Under the rapid emissions reduction scenario (RCP 2.6), these events would occur nearly twice as often. For the scenario assuming continued increases in emissions (RCP 8.5), these events would occur up to five times as often. (Figure source: NOAA NCDC / CICS-NC).

Key Message 7: Extreme Weather

There have been changes in some types of extreme weather events over the last several decades. Heat waves have become more frequent and intense, especially in the West. Cold waves have become less frequent and intense across the nation. There have been regional trends in floods and droughts. Droughts in the Southwest and heat waves everywhere are projected to become more intense, and cold waves less intense everywhere.

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Heat waves are periods of abnormally hot weather lasting days to weeks.[48] Heat waves have generally become more frequent across the U.S. in recent decades, with western regions (including Alaska) setting records for numbers of these events in the 2000s. Tree ring data suggests that the drought over the last decade in the western U.S. represents the driest conditions in 800 years.[1,56] Most other regions in the country had their highest number of short-duration heat waves in the 1930s, when the multi-year severe drought of the Dust Bowl period, combined with deleterious land-use practices,[57] contributed to the intense summer heat through depletion of soil moisture and reduction of the moderating effects of evaporation.[58] However, the recent prolonged (multi-month) extreme heat has been unprecedented since the start of reliable instrumental records in 1895. The recent heat waves and droughts in Texas (2011) and the Midwest (2012) set records for highest monthly average temperatures, exceeding in some cases records set in the 1930s, including the highest monthly contiguous U.S. temperature on record (July 2012, breaking the July 1936 record) and the hottest summers on record in several states (New Mexico, Texas, Oklahoma, and Louisiana in 2011 and Colorado and Wyoming in 2012). For the spring and summer months, 2012 had the second largest area of record-setting monthly average temperatures, including a 26-state area from Wyoming to the East Coast. The summer (June-August) temperatures of 2012 ranked in the hottest 10% of the 118-year period of record in 28 states covering the Rocky Mountain states, the Great Plains, the Upper Midwest, and the Northeast. The new records included both hot daytime maximum temperatures and warm nighttime minimum temperatures.[59] Corresponding with this increase in extreme heat, the number of extreme cold waves has reached the lowest levels on record (since 1895).

Many more high temperature records are being broken as compared to low temperature records over the past three to four decades – another indicator of a warming climate.[60] The number of record low monthly temperatures has declined to the lowest levels since 1911, while the number of record high monthly temperatures has increased to the highest level since the 1930s. During this same period, there has been an increasing trend in persistently high nighttime temperature.[1] There are various reasons why low temperatures have increased more than high temperatures.[61]

In some areas, prolonged periods of record high temperatures associated with droughts contribute to dry conditions that are driving wildfires.[62] The meteorological situations that cause heat waves are a natural part of the climate system. Thus the timing and location of individual events may be largely a natural phenomenon, although even these may be affected by human-induced climate change.[63] However, there is emerging evidence that most of the increases of heat wave severity over the U.S. are likely due to human activity,[64] with a detectable human influence in recent heat waves in the southern Great Plains[1,65] as well as in Europe[7,62] and Russia.[60,66,67] The summer 2011 heat wave and drought in Texas was primarily driven by precipitation deficits, but the human contribution to climate change approximately doubled the probability that the heat was record-breaking.[68] So while an event such as this Texas heat wave and drought could be triggered by a naturally occurring event such as a deficit in precipitation, the chances for record-breaking temperature extremes has increased and will continue to increase as the global climate warms. Generally, the changes in climate are increasing the likelihood for these types of severe events.

The number of extremely hot days is projected to continue to increase over much of the United States, especially by late century. Summer temperatures are projected to continue rising, and a reduction of soil moisture, which exacerbates heat waves, is projected for much of the western and central U.S. in summer. Climate models project that the same summertime temperatures that ranked among the hottest 5% in 1950-1979 will occur at least 70% of the time by 2035-2064 in the U.S. if global emissions of heat-trapping gases continue to grow (as in the A2 scenario).[67] By the end of this century, what have previously been once-in-20-year extreme heat days (1-day events) are projected to occur every two or three years over most of the nation.[69,70] In other words, what now seems like an extremely hot day will become commonplace.

Projected Temperature Change of Hottest and Coldest Days

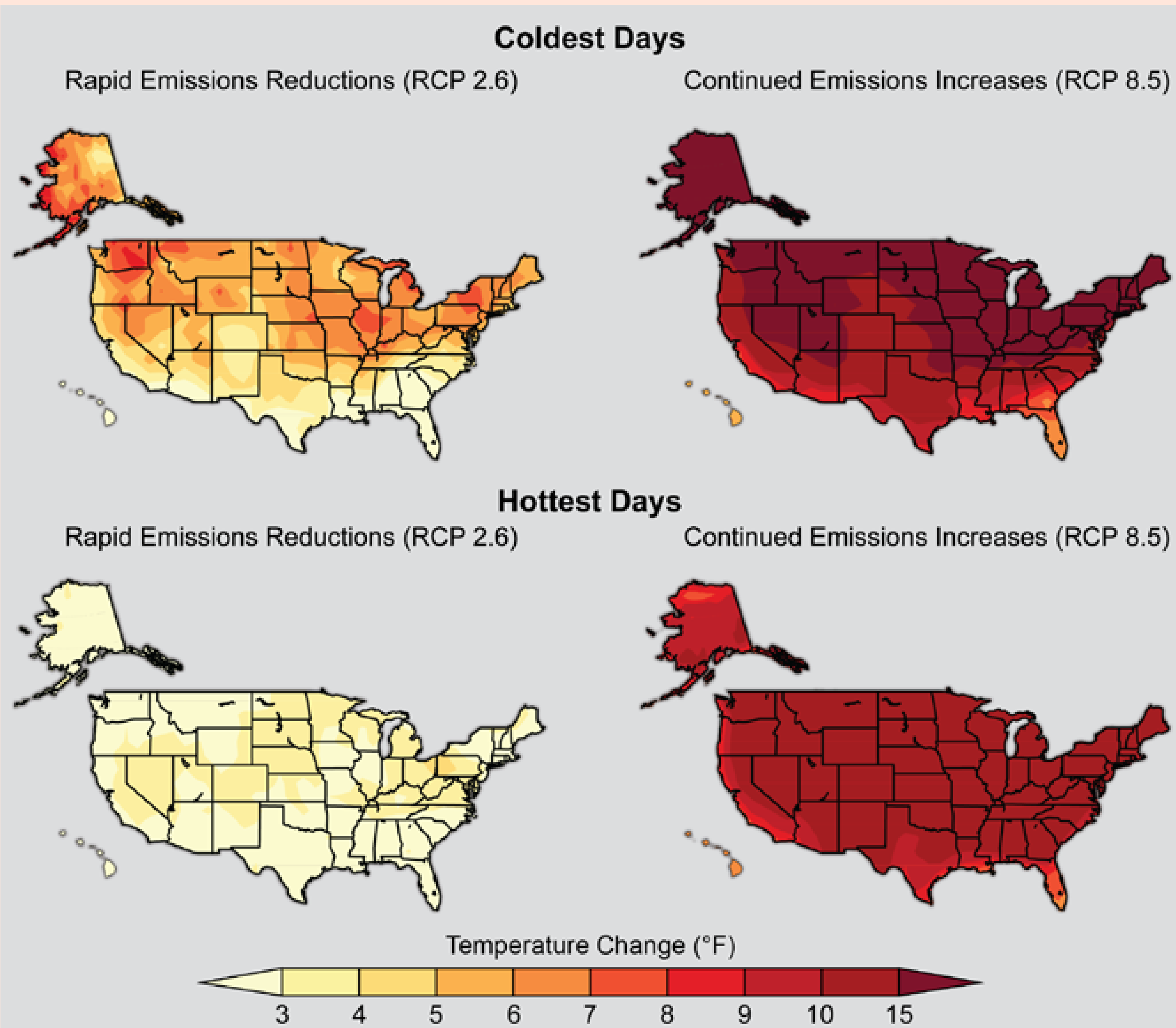


Figure 2.20. Change in surface air temperature at the end of this century (2081-2100) relative to the turn of the last century (1986-2005) on the coldest and hottest days under a scenario that assumes a rapid reduction in heat trapping gases (RCP 2.6) and a scenario that assumes continued increases in these gases (RCP 8.5). This figure shows estimated changes in the average temperature of the hottest and coldest days in each 20-year period. In other words, the hottest days will get even hotter, and the coldest days will be less cold. (Figure source: NOAA NCDC / CICS-NC).

There are significant trends in the magnitude of river flooding in many parts of the United States. When averaged over the entire nation, however, the increases and decreases cancel each other out and show no national level trend.[71] River flood magnitudes have decreased in the Southwest and increased in the eastern Great Plains, parts of the Midwest, and from the northern Appalachians into New England.[48] Figure 2.21 shows increasing trends in floods in green and decreasing trends in brown. The magnitude of these trends is illustrated by the size of the triangles.

Trends in Flood Magnitude

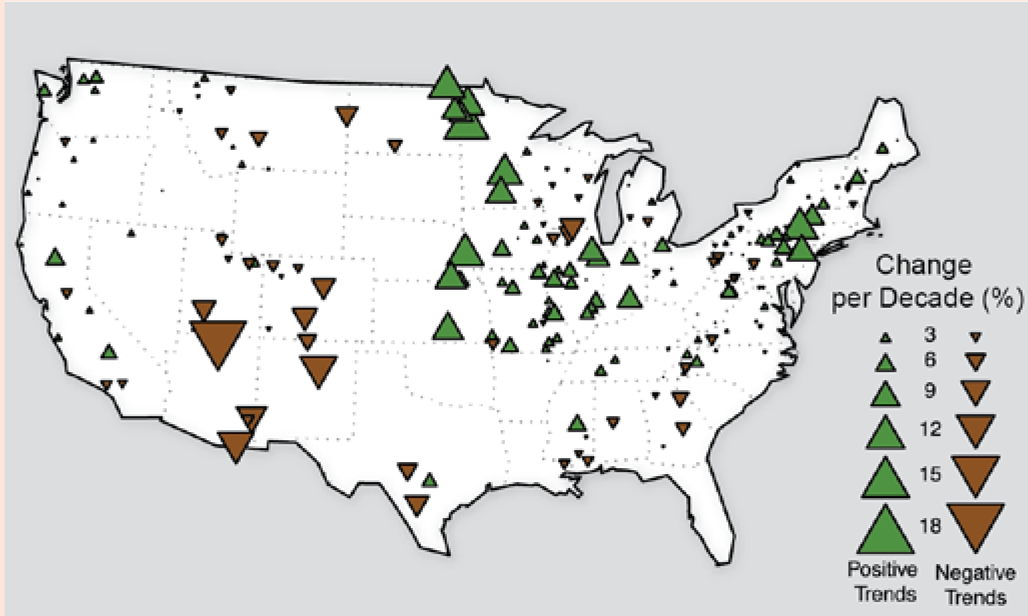


Figure 2.21. Trend magnitude (triangle size) and direction (green = increasing trend, brown = decreasing trend) of annual flood magnitude from the 1920s through 2008. Local areas can be affected by land-use change (such as dams). Most significant are the increasing trend for floods in the Midwest and Northeast and the decreasing trend in the Southwest. (Figure source: Peterson et al. 2013[48]).

These regional river flood trends are qualitatively consistent with trends in climate conditions associated with flooding. For example, average annual precipitation has increased in the Midwest and Northeast and decreased in the Southwest (Figure 2.12).[48] Recent soil moisture trends show general drying in the Southwest and moistening in the Northeast and northern Great Plains and Midwest (Ch 3: Water, Figure 3.2). These trends are in general agreement with the flood trends. Although there is a strong national upward trend in extreme precipitation and not in river flooding, the regional variations are similar. Extreme precipitation has been increasing strongly in the Great Plains, Midwest, and Northeast, where river flooding increases have been observed, and there is little trend in the Southwest, where river flooding has decreased. An exact correspondence is not necessarily expected since the seasonal timing of precipitation events makes a difference in whether river flooding occurs. The increase in extreme precipitation events has been concentrated in the summer and fall[52] when soil moisture is seasonally low and soils can absorb a greater fraction of rainfall. By contrast, many of the annual flood events occur in the spring when soil moisture is high. Thus, additional extreme rainfall events in summer and fall may not create sufficient runoff for the resulting streamflow to exceed spring flood magnitudes. However, these extreme precipitation events are often associated with local flash floods, a leading cause of death due to weather events (see "Flood Factors and Flood Types" in Ch. 3: Water).

Research into the effects of human-induced climate change on flood events is relatively new. There is evidence of a detectable human influence in recent flooding events in England and Wales[13] and in other specific events around the globe during 2011.[48] In general, heavier rains lead to a larger fraction of rainfall running off and, depending on the surface conditions, more potential for flooding.

Higher temperatures lead to increased rates of evaporation, including more loss of moisture through plant leaves. Even in areas where precipitation does not decrease, these increases in surface evaporation and loss of water from plants lead to more rapid drying of soils if the effects of higher temperatures are not offset by other changes (such as in wind speed or humidity).[72] As soil dries out, a larger proportion of the incoming heat from the sun goes into heating the soil and adjacent air rather than evaporating its moisture, resulting in hotter summers under drier climatic conditions.[73] Under higher emissions scenarios, widespread drought is projected to become more common over most of the central and southern United States.[56,74,75,76,77]

Projected Changes in Soil Moisture for the Western U.S.

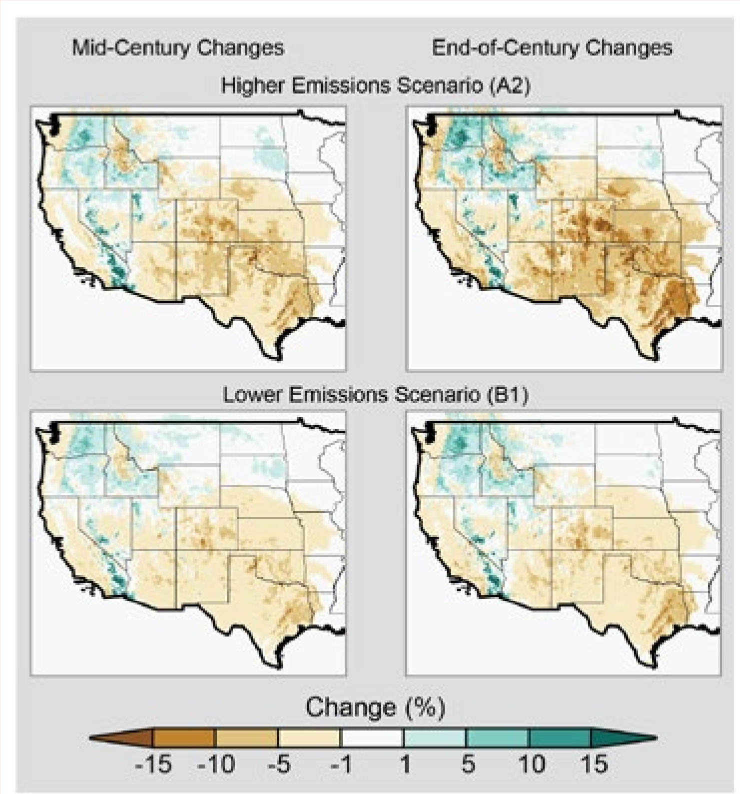


Figure 2.22. Average change in soil moisture compared to 1971-2000, as projected for the middle of this century (2041-2070) and late this century (2071-2100) under two emissions scenarios, a lower scenario (B1) and a higher scenario (A2).[75,77] The future drying of soils in most areas simulated by this sophisticated hydrologic model (Variable Infiltration Capacity or VIC model) is consistent with the future drought increases using the simpler Palmer Drought Severity Index (PDSI) metric. Only the western U.S. is displayed because model simulations were only run for this area. (Figure source: NOAA NCDC / CICS-NC).

Key Message 8: Changes in Hurricanes

The intensity, frequency, and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Category 4 and 5) hurricanes, have all increased since the early 1980s. The relative contributions of human and natural causes to these increases are still uncertain. Hurricane-associated storm intensity and rainfall rates are projected to increase as the climate continues to warm.

There has been a substantial increase in most measures of Atlantic hurricane activity since the early 1980s, the period during which high-quality satellite data are available.[78,79] These include measures of intensity, frequency, and duration as well as the number of strongest (Category 4 and 5) storms. The ability to assess longer-term trends in hurricane activity is limited by the quality of available data. The historic record of Atlantic hurricanes dates back to the mid-1800s, and indicates other decades of high activity. However, there is considerable uncertainty in the record prior to the satellite era (early 1970s), and the further back in time one goes, the more uncertain the record becomes.[79]

The recent increases in activity are linked, in part, to higher sea surface temperatures in the region that Atlantic hurricanes form in and move through. Numerous factors have been shown to influence these local sea surface temperatures, including natural variability, human-induced emissions of heat-trapping gases, and particulate pollution. Quantifying the relative contributions of natural and human-caused factors is an active focus of research. Some studies suggest that natural variability, which includes the Atlantic Multidecadal Oscillation, is the dominant cause of the warming trend in the Atlantic since the 1970s,[80,81] while others argue that human-caused heat-trapping gases and particulate pollution are more important.[82]

Hurricane development, however, is influenced by more than just sea surface temperature. How hurricanes develop also depends on how the local atmosphere responds to changes in local sea surface temperatures, and this atmospheric response depends critically on the *cause* of the change.[83] For example, the atmosphere responds differently when local sea surface temperatures increase due to a local decrease of particulate pollution that allows more sunlight through to warm the ocean, versus when sea surface temperatures increase more uniformly around the world due to increased amounts of human-caused heat-trapping gases.[80,84] So the link between hurricanes and ocean temperatures is complex. Improving our

Observed Trends in Hurricane Power Dissipation

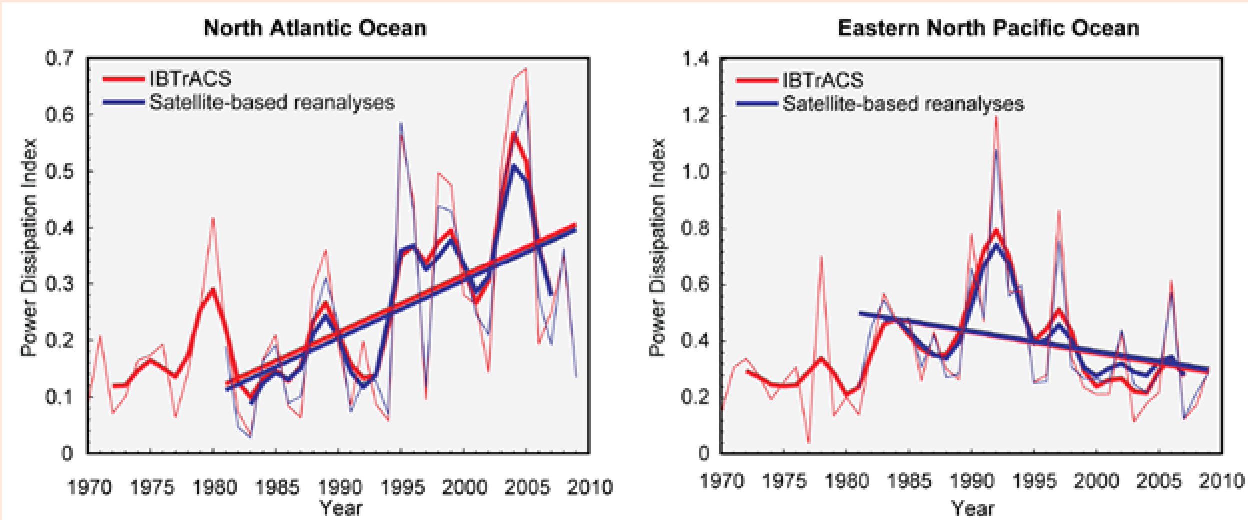


Figure 2.23. Recent variations of the Power Dissipation Index (PDI) in the North Atlantic and eastern North Pacific Oceans. PDI is an aggregate of storm intensity, frequency, and duration and provides a measure of total hurricane power over a hurricane season. There is a strong upward trend in Atlantic PDI, and a downward trend in the eastern North Pacific, both of which are well-supported by the reanalysis. Separate analyses (not shown) indicate a significant increase in the strength and in the number of the strongest hurricanes (Category 4 and 5) in the North Atlantic over this same time period. The PDI is calculated from historical data (IBTrACS[92]) and from reanalyses using satellite data (UW/NCDC & ADT-HURSAT[93,94]). IBTrACS is the International Best Track Archive for Climate Stewardship, UW/NCDC is the University of Wisconsin/NOAA National Climatic Data Center satellite-derived hurricane intensity dataset, and ADT-HURSAT is the Advanced Dvorak Technique–Hurricane Satellite dataset (Figure source: adapted from Kossin et al. 2007[93]).

understanding of the relationships between warming tropical oceans and tropical cyclones is another active area of research.

Changes in the average length and positions of Atlantic storm tracks are also associated with regional climate variability.[85] The locations and frequency of storms striking land have been argued to vary in opposing ways than basin-wide frequency. For example, fewer storms have been observed to strike land during warmer years even though overall activity is higher than average,[86] which may help to explain the lack of any clear trend in landfall frequency along the U.S. eastern and Gulf coasts.[87,88] Climate models also project changes in hurricane tracks and where they strike land.[89] The specific characteristics of the changes are being actively studied.

Other measures of Atlantic storm activity are projected to change as well.[87,90,91] By late this century, models, on average, project a slight decrease in the annual number of tropical cyclones, but an increase in the number of the strongest (Category 4 and 5) hurricanes. These projected changes are based on an average of projections from a number of individual models, and they represent the most likely outcome. There is some uncertainty in this as the individual models do not always agree on the amount of projected change, and some models may project an increase where others project a decrease. The models are in better agreement when projecting changes in hurricane precipitation – almost all existing studies project greater rainfall rates in hurricanes in a warmer climate, with projected increases of about 20% averaged near the center of hurricanes.

North Atlantic hurricanes have increased in intensity, frequency, and duration since the early 1980s.

Key Message 9: Changes in Storms

Winter storms have increased in frequency and intensity since the 1950s, and their tracks have shifted northward over the United States. Other trends in severe storms, including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds, are uncertain and are being studied intensively.

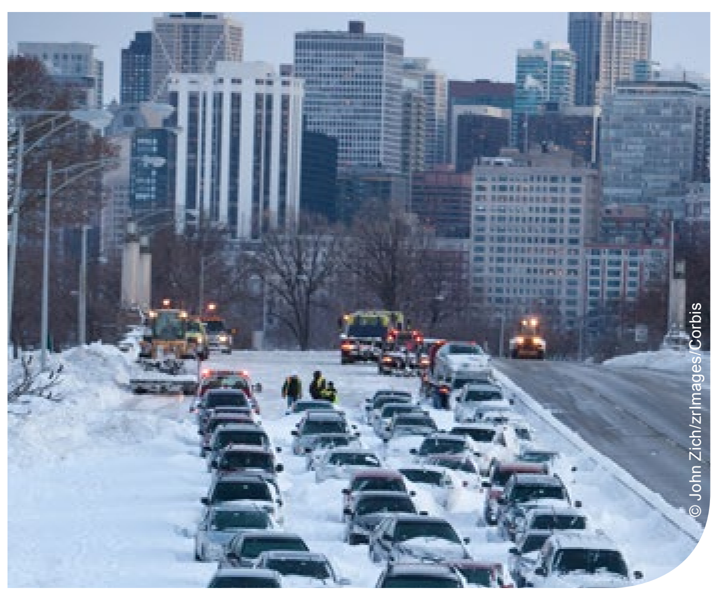
Trends in the occurrences of storms, ranging from severe thunderstorms to winter storms to hurricanes, are subject to much greater uncertainties than trends in temperature and variables that are directly related to temperature (such as snow and ice cover, ocean heat content, and sea level). Recognizing that the impacts of changes in the frequency and intensity of these storms can easily exceed the impacts of changes in average temperature or precipitation, climate scientists are actively researching the connections between climate change and severe storms. There has been a sizeable upward trend in the number of storms causing large financial and other losses.[95] However, there are societal contributions to this trend, such as increases in population and wealth.[52]

Severe Convective Storms

Tornadoes and other severe thunderstorm phenomena frequently cause as much annual property damage in the U.S. as do hurricanes, and often cause more deaths. Recent research has yielded insights into the connections between global warming and the factors that cause tornadoes and severe thunderstorms (such as atmospheric instability and increases in wind speed with altitude[96]). Although these relationships are still being explored, a recent study suggests a projected increase in the frequency of conditions favorable for severe thunderstorms.[97]

Winter Storms

For the entire Northern Hemisphere, there is evidence of an increase in both storm frequency and intensity during the cold season since 1950,[98] with storm tracks having shifted slightly towards the poles.[99,100] Extremely heavy snowstorms increased in number during the last century in northern and eastern parts of the United States, but have been less frequent since 2000.[52,101] Total seasonal snowfall has generally decreased in southern and some western areas,[102] increased in the northern Great Plains and Great Lakes region,[102,103] and not changed in other areas, such as the Sierra Nevada, although snow is melting earlier in the year and more precipitation is falling as rain versus snow.[104] Very snowy winters have generally been decreasing in frequency in most regions over the last 10 to 20 years, although the Northeast has been seeing a normal number of such winters.[105] Heavier-than-normal snowfalls recently observed in the Midwest and Northeast U.S. in some years, with little snow in other years, are consistent with indications of increased blocking (a large scale pressure pattern with little or no movement) of the wintertime circulation of the Northern Hemisphere.[106] However, conclusions about trends in blocking have been found to depend on the method of analysis,[107] so the assessment and attribution of trends in blocking remains an active research area. Overall snow cover has decreased in the Northern Hemisphere, due in part to higher temperatures that shorten the time snow spends on the ground.[108]



Variation of Storm Frequency and Intensity during the Cold Season (November – March)

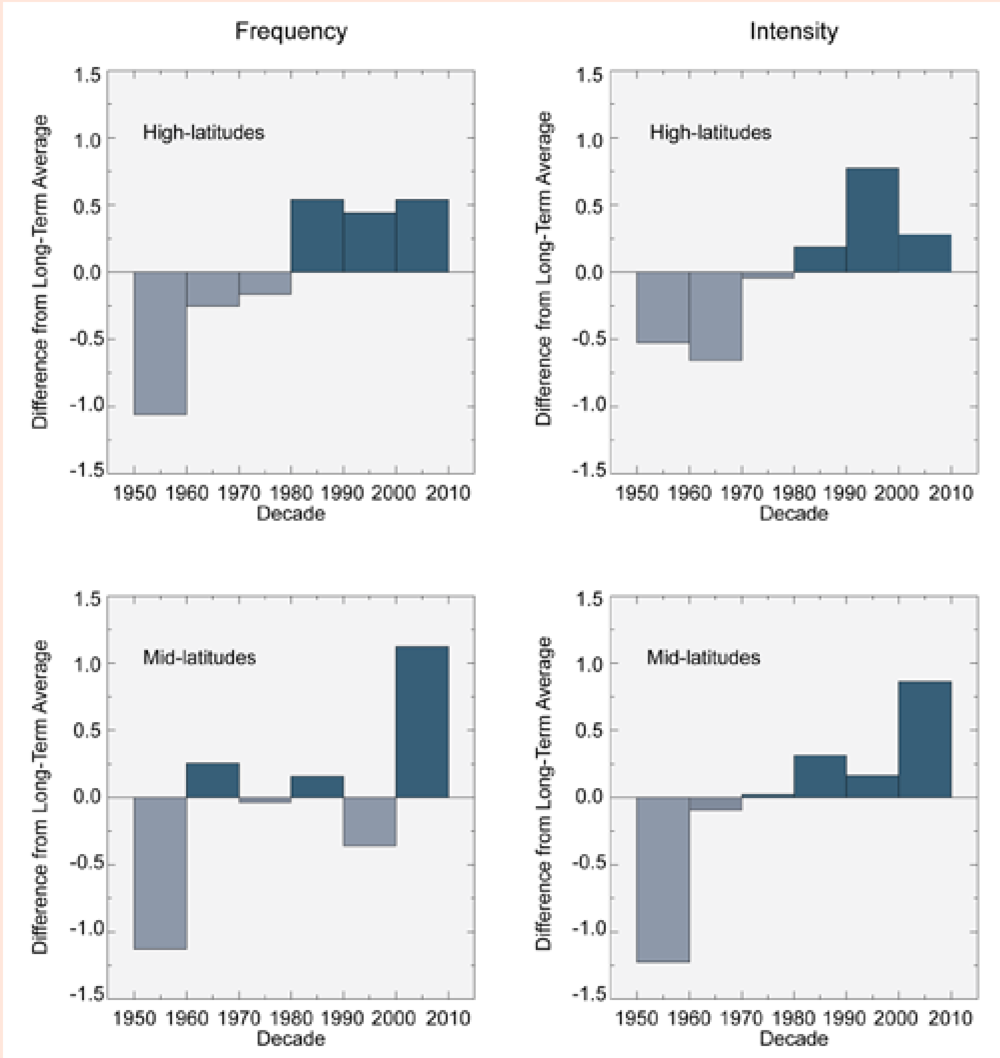


Figure 2.24. Variation of winter storm frequency and intensity during the cold season (November-March) for high latitudes (60-90°N) and mid-latitudes (30-60°N) of the Northern Hemisphere over the period 1949-2010. The bar for each decade represents the difference from the long-term average. Storm frequencies have increased in middle and high latitudes, and storm intensities have increased in middle latitudes. (Figure source: updated from CCSP 2008[109]).

Key Message 10: Sea Level Rise

Global sea level has risen by about 8 inches since reliable record keeping began in 1880. It is projected to rise another 1 to 4 feet by 2100.

The oceans are absorbing over 90% of the increased atmospheric heat associated with emissions from human activity.[110] Like mercury in a thermometer, water expands as it warms up (this is referred to as "thermal expansion") causing sea levels to rise. Melting of glaciers and ice sheets is also contributing to sea level rise at increasing rates.[111]

Since the late 1800s, tide gauges throughout the world have shown that global sea level has risen by about 8 inches. A new data set (Figure 2.25) shows that this recent rise is much greater than at any time in at least the past 2000 years.[112] Since 1992, the rate of global sea level rise measured by satellites has been roughly twice the rate observed over the last century, providing evidence of additional acceleration.[113]

Projecting future rates of sea level rise is challenging. Even the most sophisticated climate models, which explicitly represent Earth's physical processes, cannot simulate rapid changes in ice sheet dynamics, and thus are likely to underestimate future sea level rise. In recent years, "semi-empirical" methods have been developed to project future rates of sea level rise based on a simple statistical relationship between past rates of globally averaged temperature change and sea level rise. These models suggest a range of additional sea level rise from about 2 feet to as much as 6 feet by 2100, depending on emissions scenario.[114,115,116,117] It is not clear, however, whether these statistical relationships will hold in the future, or that they fully explain historical behavior.[118] Regardless of the amount of change by 2100, however, sea level rise is expected to continue well beyond this century as a result of both past and future emissions from human activities.

North Atlantic Sea Level Change

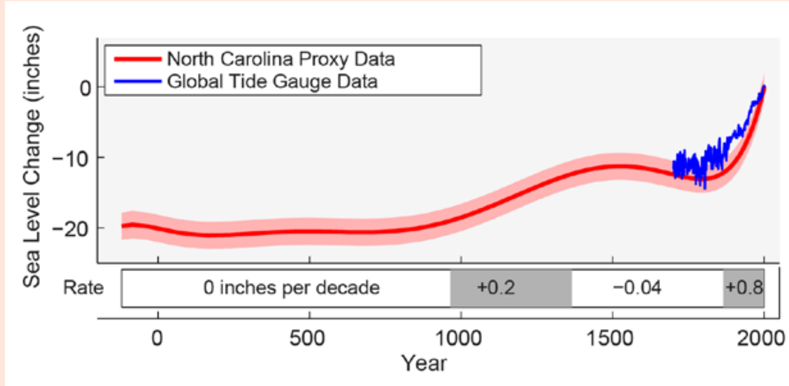


Figure 2.25. Sea level change in the North Atlantic Ocean relative to the year 2000 based on data collected from North Carolina[112] (red line, pink band shows the uncertainty range) compared with a reconstruction of global sea level rise based on tide gauge data from 1750 to present[127] (blue line). (Figure source: Adapted from Kemp et al. 2011[112]).

Scientists are working to narrow the range of sea level rise projections for this century. Recent projections show that for even the lowest emissions scenarios, thermal expansion of ocean waters[119] and the melting of small mountain glaciers[120] will result in 11 inches of sea level rise by 2100, even without any contribution from the ice sheets in Greenland and Antarctica. This suggests that about 1 foot of global sea level rise by 2100 is probably a realistic low end. On the high end, recent work suggests that 4 feet is plausible.[22,115,121] In the context of risk-based analysis, some decision makers may wish to use a wider range of scenarios, from 8 inches to 6.6 feet by 2100.[122,123] In particular, the high end of these scenarios may be useful for decision makers with a low tolerance for risk (see Figure 2.26 on global sea level rise).[122,123] Although scientists cannot yet assign likelihood to any particular scenario, in general, higher emissions scenarios that lead to more warming would be expected to lead to higher amounts of sea level rise.

Nearly 5 million people in the U.S. live within 4 feet of the local high-tide level (also known as mean higher high water). In the next several decades, storm surges and high tides could combine with sea level rise and land subsidence to further increase flooding in many of these regions.[124] Sea level rise will not stop in 2100 because the oceans take a very long time to respond to warmer conditions at the Earth's surface. Ocean waters will therefore continue to warm and sea level will continue to rise for many centuries at rates equal to or higher than that of the current century.[125] In fact, recent research has suggested that even present day carbon dioxide levels are sufficient to cause Greenland to melt completely over the next several thousand years.[126]

Past and Projected Changes in Global Sea Level Rise

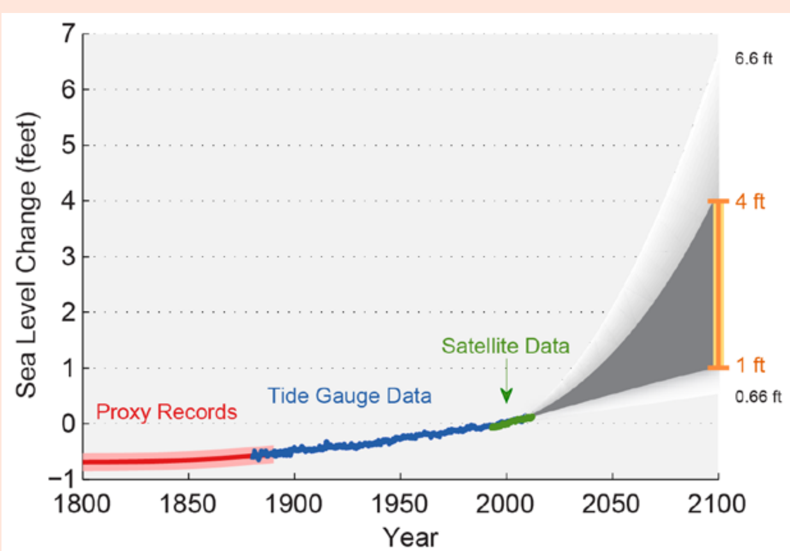


Figure 2.26. Estimated, observed, and possible future amounts of global sea level rise from 1800 to 2100, relative to the year 2000. Estimates from proxy data[112] (for example, based on sediment records) are shown in red (1800-1890, pink band shows uncertainty), tide gauge data are shown in blue for 1880-2009,[113] and satellite observations are shown in green from 1993 to 2012.[128] The future scenarios range from 0.66 feet to 6.6 feet in 2100.[123] These scenarios are not based on climate model simulations, but rather reflect the range of possible scenarios based on other scientific studies. The orange line at right shows the currently projected range of sea level rise of 1 to 4 feet by 2100, which falls within the larger risk-based scenario range. The large projected range reflects uncertainty about how glaciers and ice sheets will react to the warming ocean, the warming atmosphere, and changing winds and currents. As seen in the observations, there are year-to-year variations in the trend. (Figure source: Adapted from Parris et al. 2012,[123] with contributions from NASA Jet Propulsion Laboratory).

Key Message 11: Melting Ice

Rising temperatures are reducing ice volume and surface extent on land, lakes, and sea. This loss of ice is expected to continue. The Arctic Ocean is expected to become essentially ice free in summer before mid-century.

Rising temperatures across the U.S. have reduced lake ice, sea ice, glaciers, and seasonal snow cover over the last few decades.[111] In the Great Lakes, for example, total winter ice coverage has decreased by 63% since the early 1970s.[172] This includes the entire period since satellite data became available. When the record is extended back to 1963 using pre-satellite data,[129] the overall trend is less negative because the Great Lakes region experienced several extremely cold winters in the 1970s.

Sea ice in the Arctic has also decreased dramatically since the late 1970s, particularly in summer and autumn. Since the satellite record began in 1978, minimum Arctic sea ice extent (which occurs in early to mid-September) has decreased by more than 40%.[131] This decline is unprecedented in the historical record, and the reduction of ice volume and thickness is even greater. Ice thickness decreased by more than 50% from 1958-1976 to 2003-2008,[132] and the percentage of the March ice cover made up of thicker ice (ice that has survived a summer melt season) decreased from 75% in the mid-1980s to 45% in 2011.[133] Recent analyses indicate a decrease of 36% in autumn sea ice volume over the past decade.[134] The 2012 sea ice minimum broke the preceding record (set in 2007) by more than 200,000 square miles. Ice loss increases Arctic warming by replacing white, reflective ice with dark water that absorbs more energy from the sun. More open water can also increase snowfall over northern land areas[135] and increase the north-south meanders of the jet stream, consistent with the occurrence of unusually cold and snowy winters at mid-latitudes in several recent years.[106,135] Significant uncertainties remain at this time in interpreting the effect of Arctic ice changes on mid-latitudes.[107]

The loss of sea ice has been greater in summer than in winter. The Bering Sea, for example, has sea ice only in the winter-spring portion of the year, and shows no trend in surface area covered by ice over the past 30 years. However, seasonal ice in the Bering Sea and elsewhere in the Arctic is thin and susceptible to rapid melt during the following summer.

The seasonal pattern of observed loss of Arctic sea ice is generally consistent with simulations by global climate models, in which the extent of sea ice decreases more rapidly in summer than in winter. However, the models tend to underestimate the amount of decrease since 2007. Projections by these models indicate that the Arctic Ocean is expected to become essentially ice-free in summer before mid-century under scenarios that assume continued growth in global emissions, although sea ice would still form in winter.[136,137] Models that best match historical trends project a nearly sea ice-free Arctic in summer by the 2030s,[138] and extrapolation of the present observed trend suggests an even earlier ice-free Arctic in summer.[139] However, even during a long-term decrease, occasional temporary increases in Arctic summer sea ice can be expected over timescales of a decade or so because of natural variability.[140] The projected reduction of winter sea ice is only about 10% by 2030,[141] indicating that the Arctic will shift to a more seasonal sea ice pattern. While this ice will be thinner, it will cover much of the same area now covered by sea ice in winter.

While the Arctic is an ocean surrounded by continents, Antarctica is a continent surrounded by ocean. Nearly all of the sea ice in the Antarctic melts each summer, and changes there are more complicated than in the Arctic. While Arctic sea ice has

Ice Cover in the Great Lakes

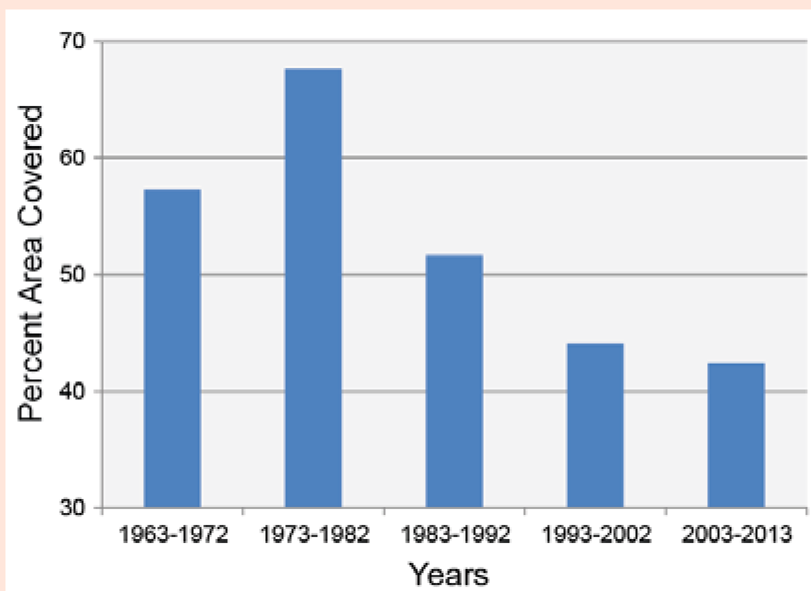


Figure 2.27. Bars show decade averages of annual maximum Great Lakes ice coverage from the winter of 1962-1963, when reliable coverage of the entire Great Lakes began, to the winter of 2012-2013. Bar labels indicate the end year of the winter; for example, 1963-1972 indicates the winter of 1962-1963 through the winter of 1971-1972. Only the most recent period includes the eleven years from 2003 to 2013. (Data updated from Bai and Wang, 2012[130]).

Decline in Arctic Sea Ice Extent

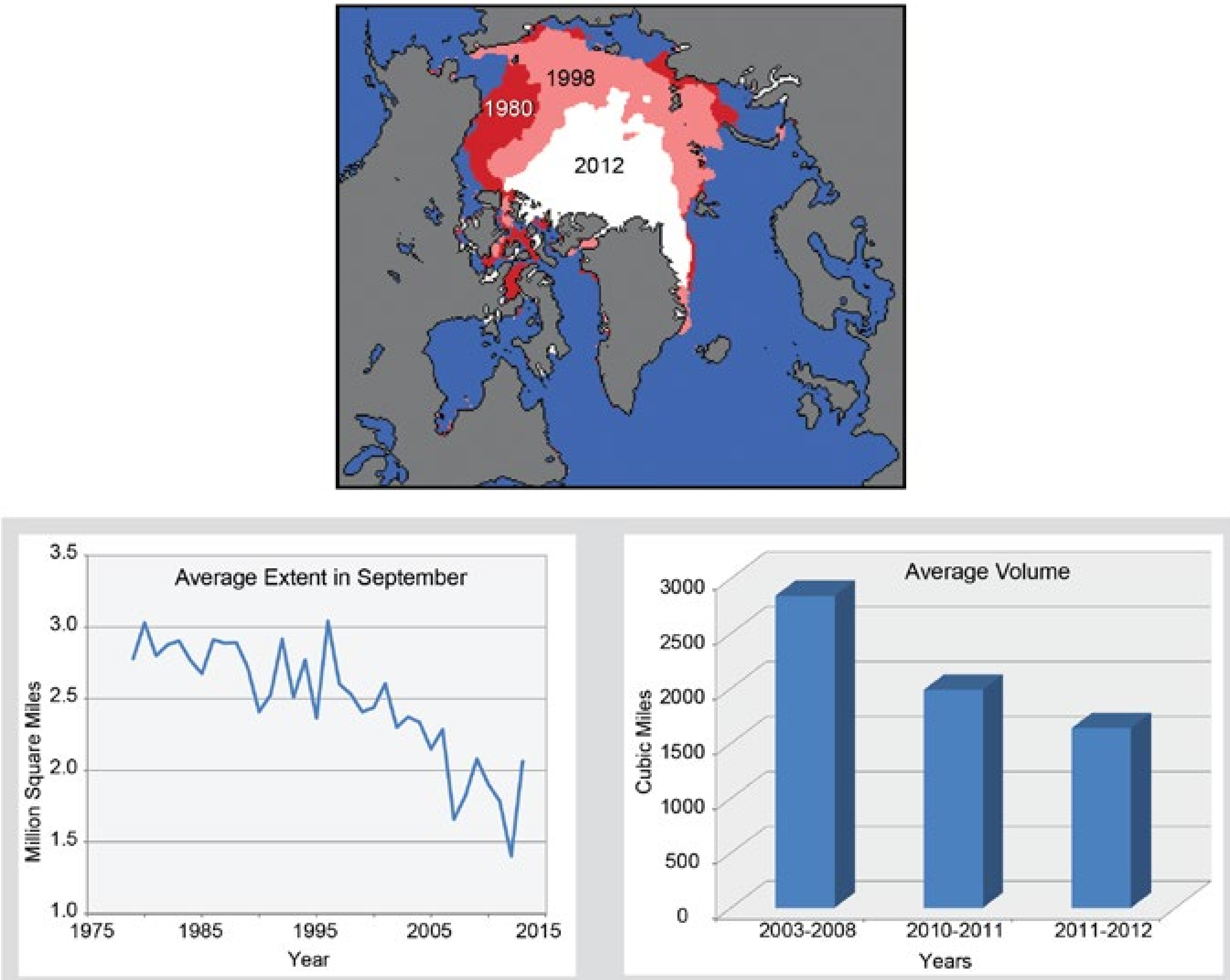


Figure 2.28. Summer Arctic sea ice has declined dramatically since satellites began measuring it in 1979. The extent of sea ice in September 2012, shown in white in the top figure, was more than 40% below the median for 1979-2000. The graph on the bottom left shows annual variations in September Arctic sea ice extent for 1979-2013. It is also notable that the ice has become much thinner in recent years, so its total volume (bottom right) has declined even more rapidly than the extent.[111] (Figure and data from National Snow and Ice Data Center).

been strongly decreasing, there has been a slight increase in sea ice in Antarctica.[142] Explanations for this include changes in winds that directly affect ice drift as well as the properties of the surrounding ocean,[143] and that winds around Antarctica may have been affected by stratospheric ozone depletion.[144]

Snow cover on land has decreased over the past several decades,[145] especially in late spring.[146] Each of five recent years (2008-2012) has set a new record for minimum snow extent in June in Eurasia, as did three of those five years in North America.

The surface of the Greenland Ice Sheet has been experiencing summer melting over increasingly large areas during the past several decades. In the decade of the 2000s, the daily melt area summed over the warm season was double the corresponding amounts of the 1970s,[147] culminating in summer surface melt that was far greater (97% of the Greenland Ice Sheet area) in 2012 than in any year since the satellite record began in 1979. More importantly, the rate of mass loss from the Greenland Ice Sheet's marine-terminating outlet glaciers has accelerated in recent decades, leading to predictions that the proportion of global sea level rise coming from Greenland will continue to increase.[148] Glaciers terminating on ice shelves and on land are also losing mass, but the rate of loss has not accelerated over the past decade.[149] As discussed in Key Message 10, the dynamics of the Greenland Ice Sheet are generally not included in present global climate models and sea level rise projections.

Glaciers are retreating and/or thinning in Alaska and in the lower 48 states. In addition, permafrost temperatures are increasing over Alaska and much of the Arctic. Regions of discontinuous permafrost in interior Alaska (where annual average soil temperatures are already close to 32°F) are highly vulnerable to thaw. Thawing permafrost releases carbon dioxide and methane – heat-trapping gases that contribute to even more warming. Recent estimates suggest that the potential release of carbon from permafrost soils could add as much as 0.4ºF to 0.6ºF of warming by 2100.[150] Methane emissions have been detected from Alaskan lakes underlain by permafrost,[151] and measurements suggest potentially even greater releases from thawing methane hydrates in the Arctic continental shelf of the East Siberian Sea.[152] However, the response times of Arctic methane hydrates to climate change are quite long relative to methane's lifetime in the atmosphere (about a decade).[153] More generally, the importance of Arctic methane sources relative to other methane sources, such as wetlands in warmer climates, is largely unknown. The potential for a self-reinforcing feedback between permafrost thawing and additional warming contributes additional uncertainty to the high end of the range of future warming. The projections of future climate shown throughout this report do not include the additional increase in temperature associated with this thawing.

Projected Arctic Sea Ice Decline

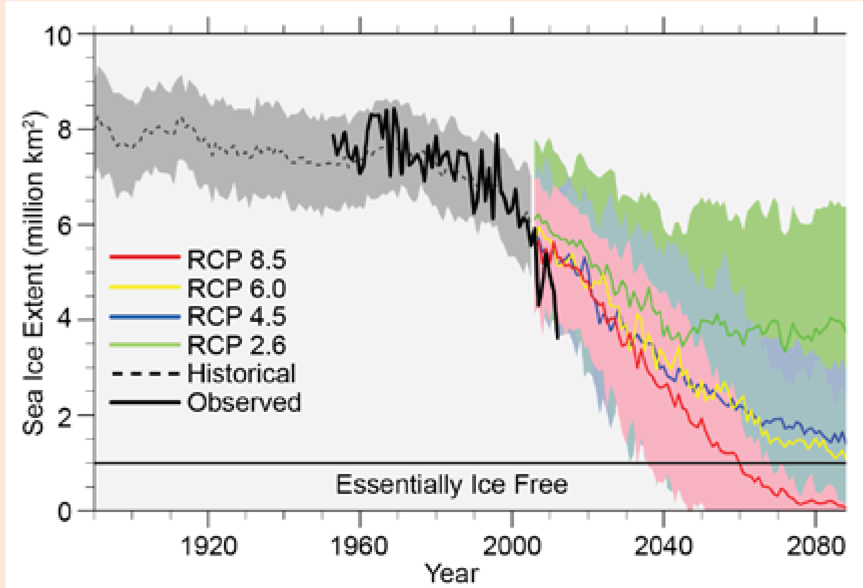


Figure 2.29. Model simulations of Arctic sea ice extent for September (1900-2100) based on observed concentrations of heat-trapping gases and particles (through 2005) and four scenarios. Colored lines for RCP scenarios are model averages (CMIP5) and lighter shades of the line colors denote ranges among models for each scenario. Dotted gray line and gray shading denotes average and range of the historical simulations through 2005. The thick black line shows observed data for 1953-2012. These newer model (CMIP5) simulations project more rapid sea ice loss compared to the previous generation of models (CMIP3) under similar forcing scenarios, although the simulated September ice losses under all scenarios still lag the observed loss of the past decade. Extrapolation of the present observed trend suggests an essentially ice-free Arctic in summer before mid-century.[139] The Arctic is considered essentially ice-free when the areal extent of ice is less than one million square kilometers. (Figure source: adapted from Stroeve et al. 2012[136]).

Key Message 12: Ocean Acidification

The oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually and are becoming more acidic as a result, leading to concerns about intensifying impacts on marine ecosystems.

As human-induced emissions of carbon dioxide (CO_2) build up in the atmosphere, excess CO_2 is dissolving into the oceans where it reacts with seawater to form carbonic acid, lowering ocean pH levels ("acidification") and threatening a number of marine ecosystems.[154] Currently, the oceans absorbs about a quarter of the CO_2 humans produce every year.[155] Over the last 250 years, the oceans have absorbed 560 billion tons of CO_2, increasing the acidity of surface waters by 30%.[156,157,158] Although the average oceanic pH can vary on interglacial timescales,[156] the current observed rate of change is roughly 50 times faster than known historical change.[159,160] Regional factors such as coastal upwelling,[161] changes in discharge rates from rivers and glaciers,[162] sea ice loss,[163] and urbanization[164] have created "ocean acidification hotspots" where changes are occurring at even faster rates.

The acidification of the oceans has already caused a suppression of carbonate ion concentrations that are critical for marine calcifying animals such as corals, zooplankton, and shellfish. Many of these animals form the foundation of the marine food web. Today, more than a billion people worldwide rely on food from the ocean as their primary source of protein. Ocean acidification puts this important resource at risk.

Observations have shown that the northeastern Pacific Ocean, including the Arctic and sub-Arctic seas, is particularly susceptible to significant shifts in pH and calcium carbonate saturation levels. Recent analyses show that large areas of the oceans along the U.S. west coast,[157,165] the Bering Sea, and the western Arctic Ocean[158,166] will become difficult for calcifying animals within the next 50 years. In particular, animals that form calcium carbonate shells, including corals, crabs, clams, oysters, and tiny free-swimming snails called pteropods, could be particularly vulnerable, especially during the larval stage.[167,168,169]

Projections indicate that in higher emissions pathways, such as SRES A2 or RCP 8.5, current pH could be reduced from the current level of 8.1 to as low as 7.8 by the end of the century.[158] Such large changes in ocean pH have probably not been experienced on the planet for the past 100 million years, and it is unclear whether and how quickly ocean life could adapt to such rapid acidification.[159]

As Oceans Absorb CO_2, They Become More Acidic

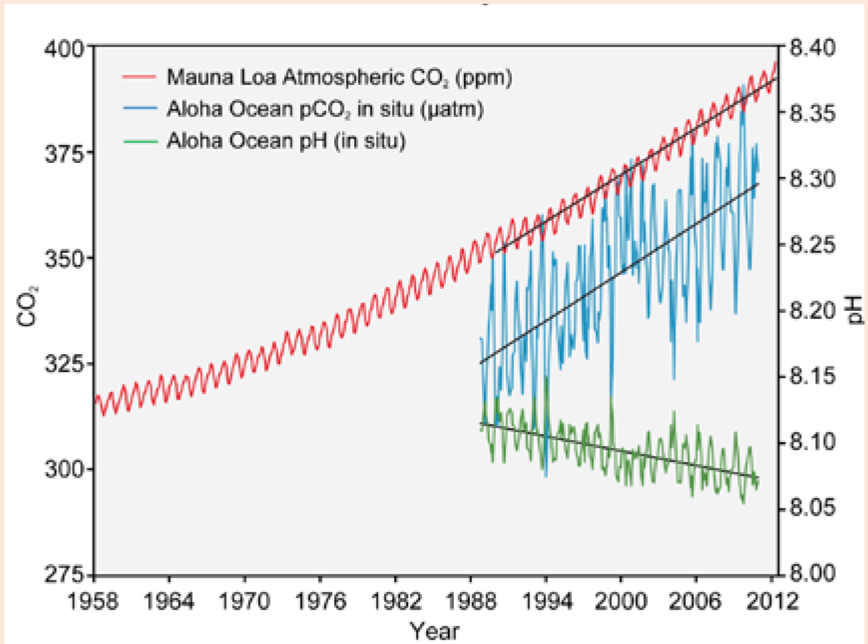


Figure 2.30. The correlation between rising levels of CO_2 in the atmosphere (red) at Mauna Loa and rising CO_2 levels (blue) and falling pH (green) in the nearby ocean at Station Aloha. As CO_2 accumulates in the ocean, the water becomes more acidic (the pH declines). (Figure source: modified from Feely et al. 2009[157]).

Shells Dissolve in Acidified Ocean Water

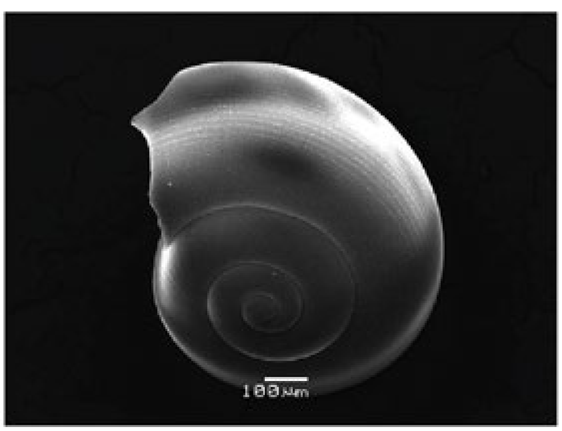


Figure 2.31. Pteropods, or "sea butterflies," are free-swimming sea snails about the size of a small pea. Pteropods are eaten by marine species ranging in size from tiny krill to whales and are an important source of food for North Pacific juvenile salmon. The photos above show what happens to a pteropod's shell in seawater that is too acidic. The left panel shows a shell collected from a live pteropod from a region in the Southern Ocean where acidity is not too high. The shell on the right is from a pteropod collected in a region where the water is more acidic (Photo credits: (left) Bednaršek et al. 2012;[168] (right) Nina Bednaršek).

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages

Development of the key messages involved discussions of the lead authors and accompanying analyses conducted via one in-person meeting plus multiple teleconferences and email exchanges from February thru September 2012. The authors reviewed 80 technical inputs provided by the public, as well as other published literature, and applied their professional judgment.

Key message development also involved the findings from four special workshops that related to the latest scientific understanding of climate extremes. Each workshop had a different theme related to climate extremes, had approximately 30 attendees (the CMIP5 meeting had more than 100), and the workshops resulted in a paper.[55] The first workshop was held in July 2011, titled Monitoring Changes in Extreme Storm Statistics: State of Knowledge.[52] The second was held in November 2011, titled Forum on Trends and Causes of Observed Changes in Heatwaves, Coldwaves, Floods, and Drought.[48] The third was held in January 2012, titled Forum on Trends in Extreme Winds, Waves, and Extratropical Storms along the Coasts.[98] The fourth, the CMIP5 results workshop, was held in March 2012 in Hawai'i, and resulted in an analysis of CMIP5 results relative to climate extremes in the United States.[55]

The Chapter Author Team's discussions were supported by targeted consultation with additional experts. Professional expertise and judgment led to determining "key vulnerabilities." A consensus-based approach was used for final key message selection.

Key message #1 Traceable Account

Global climate is changing and this change is apparent across a wide range of observations. The global warming of the past 50 years is primarily due to human activities.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the climate science literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Evidence for changes in global climate arises from multiple analyses of data from in-situ, satellite, and other records undertaken by many groups over several decades.[3] Changes in the mean state have been accompanied by changes in the frequency and nature of extreme events.[4] A substantial body of analysis comparing the observed changes to a broad range of climate simulations consistently points to the necessity of invoking human-caused changes to adequately explain the observed climate system behavior.[5,7] The influence of human impacts on the climate system has also been observed in a number of individual climate variables.[6,12,13,14,15,16,17] A discussion of the slowdown in temperature increase with associated references (for example, Balmaseda et al. 2013; Easterling and Wehner 2009[19,27]) is included in the chapter.

The Climate Science Supplement Appendix provides further discussion of types of emissions or heat-trapping gases and particles, and future projections of human-related emissions. Supplemental Message 4 of the Appendix provides further details on attribution of observed climate changes to human influence.

New information and remaining uncertainties

Key remaining uncertainties relate to the precise magnitude and nature of changes at global, and particularly regional, scales, and especially for extreme events and our ability to simulate and attribute such changes using climate models. Innovative new approaches to climate data analysis, continued improvements in climate modeling, and instigation and maintenance of reference quality observation networks such as the U.S. Climate Reference Network (http://www.ncdc.noaa.gov/crn/) all have the potential to reduce uncertainties.

Assessment of confidence based on evidence

There is **very high** confidence that global climate is changing and this change is apparent across a wide range of observations, given the evidence base and remaining uncertainties. All observational evidence is consistent with a warming climate since the late 1800s.

There is **very high** confidence that the global climate change of the past 50 years is primarily due to human activities, given the evidence base and remaining uncertainties. Recent changes have been consistently attributed in large part to human factors across a very broad range of climate system characteristics.

KEY MESSAGE #2 TRACEABLE ACCOUNT

Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, and how sensitive the Earth's climate is to those emissions.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Evidence of continued global warming is based on past observations of climate change and our knowledge of the climate system's response to heat-trapping gases. Models have projected increased temperature under a number of different scenarios.[8,32,33]

That the planet has warmed is "unequivocal,"[8] and is corroborated though multiple lines of evidence, as is the conclusion that the causes are very likely human in origin (see also Appendices 3 and 4). The evidence for future warming is based on fundamental understanding of the behavior of heat-trapping gases in the atmosphere. Model simulations provide bounds on the estimates of this warming.

New information and remaining uncertainties

The trends described in the 2009 report[1] have continued, and our understanding of the data and ability to model the many facets of the climate system have increased substantially.

There are several major sources of uncertainty in making projections of climate change. The relative importance of these changes over time.

In the next few decades, the effects of natural variability will be an important source of uncertainty for climate change projections.

Uncertainty in future human emissions becomes the largest source of uncertainty by the end of this century.

Uncertainty in how sensitive the climate is to increased concentrations of heat-trapping gases is especially important beyond the next few decades. Recent evidence lends further confidence about climate sensitivity (see Appendix 3: Climate Science Supplement).

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

Uncertainty in natural climate drivers, for example how much solar output will change over this century, also affects the accuracy of projections.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **very high** that the global climate is projected to continue to change over this century and beyond.

The statement on the magnitude of the effect also has **very high** confidence.

KEY MESSAGE #3 TRACEABLE ACCOUNT

U.S. average temperature has increased by 1.3°F to 1.9°F since record keeping began in 1895; most of this increase has occurred since about 1970. The most recent decade was the nation's warmest on record. Temperatures in the United States are expected to continue to rise. Because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, uniform or smooth across the country or over time.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Evidence for the long-term increase in temperature is based on analysis of daily maximum and minimum temperature observations from the U.S. Cooperative Observer Network (http://www.nws.noaa.gov/om/coop/). With the increasing understanding of U.S. temperature measurements, a temperature increase has been observed, and temperature is projected to continue rising.[36,37,38] Observations show that the last decade was the warmest in over a century. A number of climate model simulations were performed to assess past, and to forecast future, changes in climate; temperatures are generally projected to increase across the United States.

The section entitled "Quantifying U.S. Temperature Rise" explains the rational for using the range 1.3°F to 1.9°F in the key message.

All peer-reviewed studies to date satisfying the assessment process agree that the U.S. has warmed over the past century and in the past several decades. Climate model simulations consistently project future warming and bracket the range of plausible increases.

New information and remaining uncertainties

Since the 2009 National Climate Assessment,[1] there have been substantial advances in our understanding of the U.S. temperature record (Appendix 3: Climate Science, Supplemental Message 7).[36,37,38]

A potential uncertainty is the sensitivity of temperature trends to adjustments that account for historical changes in station location, temperature instrumentation, observing practice, and siting conditions. However, quality analyses of these uncertainties have not found any major issues of concern affecting the conclusions made in the key message (Appendix 3: Climate Science, Supplemental Message 7). (for example, Williams et al. 2012[38]).

While numerous studies (for example, Fall et al. 2011; Vose et al. 2012; Williams et al. 2012[37,38]) verify the efficacy of the adjustments, the information base can be improved in the future through continued refinements to the adjustment approach. Model biases are subject to changes in physical effects on climate; for example, model biases can be affected by snow cover and hence are subject to change as a warming climate changes snow cover.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **very high** in the key message. Because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, uniform or smooth across the country or over time.

Key message #4 Traceable Account

The length of the frost-free season (and the corresponding growing season) has been increasing nationally since the 1980s, with the largest increases occurring in the western United States, affecting ecosystems and agriculture. Across the United States, the growing season is projected to continue to lengthen.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Nearly all studies to date published in the peer-reviewed literature (for example, Dragoni et al. 2011; EPA 2012; Jeong et al. 2011[40,41,43]) agree that the frost-free and growing seasons have lengthened. This is most apparent in the western United States. Peer-reviewed studies also indicate that continued lengthening will occur if concentrations of heat-trapping gases continue to rise. The magnitude of future changes based on model simulations is large in the context of historical variations.

Evidence that the length of the frost-free season is lengthening is based on extensive analysis of daily minimum temperature observations from the U.S. Cooperative Observer Network. The geographic variations in increasing number of frost-free days are similar to the regional variations in mean temperature. Separate analysis of surface data also indicates a trend towards an earlier onset of spring.[40,41,43,45]

New information and remaining uncertainties

A key issue (uncertainty) is the potential effect on observed trends of climate monitoring station inhomogeneities (differences), particularly those arising from instrumentation changes. A second key issue is the extent to which observed regional variations (more lengthening in the west/less in the east) will persist into the future.

Local temperature biases in climate models contribute to the uncertainty in projections.

Viable avenues to improving the information base are to investigate the sensitivity of observed trends to potential biases introduced by station inhomogeneities and to investigate the causes of observed regional variations.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **very high** that the length of the frost-free season (also referred to as the growing season) has been increasing nationally since the 1980s, with the largest increases occurring in the western U.S, affecting ecosystems, gardening, and agriculture. Given the evidence base, confidence is **very high** that across the U.S., the growing season is projected to continue to lengthen.

Key message #5 Traceable Account

Average U.S. precipitation has increased since 1900, but some areas have had increases greater than the national average, and some areas have had decreases. More winter and spring precipitation is projected for the northern United States, and less for the Southwest, over this century.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Evidence of long-term change in precipitation is based on analysis (for example, Kunkel et al. 2013[170]) of daily observations from the U.S. Cooperative Observer Network. Published work shows the regional differences in precipitation.[47,48] Evidence of future change is based on our knowledge of the climate system's response to heat-trapping gases and an understanding of the regional mechanisms behind the projected changes (for example, IPCC 2007[8]).

New information and remaining uncertainties

A key issue (uncertainty) is the sensitivity of observed precipitation trends to historical changes in station location, rain gauges, and observing practice. A second key issue is the ability of climate models to simulate precipitation. This is one of the more challenging aspects of modeling of the climate system, because precipitation involves not only large-scale processes that are well-resolved by models but small-scale process, such as convection, that must be parameterized in the current generation of global and regional climate models. However, our understanding of the physical basis for these changes has solidified and the newest set of climate model simulations (CMIP5) continues to show high-latitude increases and subtropical decreases in precipitation. For most of the contiguous U.S., studies[171] indicate that the models currently do not detect a robust anthropogenic influence to observed changes, suggesting that observed changes are principally of natural origins. Thus, confident projections of precipitation changes are limited to the northern and southern areas of the contiguous U.S. that are part of the global pattern of observed and robust projected changes that can be related to anthropogenic forcing. Furthermore, for the first time in the U.S. National Climate Assessment, a confidence statement is made that some projected precipitation changes are deemed small. It is incorrect to attempt to validate or invalidate climate model simulations of observed trends in these regions and/or seasons, as such simulations are not designed to forecast the precise timing of natural variations.

Shifts in precipitation patterns due to changes in other sources of air pollution, such as sulfate aerosols, are uncertain and are an active research topic.

Viable avenues to improving the information base are to investigate the sensitivity of observed trends to potential biases introduced by station changes, and to investigate the causes of observed regional variations.

A number of peer-reviewed studies (for example, McRoberts and Nielsen-Gammon 2011; Peterson et al. 2013[47,48]) document precipitation increases at the national scale as well as regional-scale increases and decreases. The variation in magnitude and pattern of future changes from climate model simulations is large relative to observed (and modeled) historical variations.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **high** that average U.S. precipitation has increased since 1900, with some areas having had increases greater than the national average, and some areas having had decreases.

Confidence is **high,** given the evidence base and uncertainties, that more winter and spring precipitation is projected for the northern U.S., and less for the Southwest, over this century in the higher emissions scenarios. Confidence is **medium** that human-induced precipitation changes will be small compared to natural variations in all seasons over large portions of the U.S. in the lower emissions scenarios. Confidence is **medium** that human-induced precipitation changes will be small compared to natural variations in the summer and fall over large portions of the U.S. in the higher emissions scenarios.

Key message #6 Traceable Account

Heavy downpours are increasing nationally, especially over the last three to five decades. Largest increases are in the Midwest and Northeast. Increases in the frequency and intensity of extreme precipitation events are projected for all U.S. regions.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Evidence that extreme precipitation is increasing is based primarily on analysis[52,55,170] of hourly and daily precipitation observations from the U.S. Cooperative Observer Network, and is supported by observed increases in atmospheric water vapor.[75] Recent publications have projected an increase in extreme precipitation events,[52,137] with some areas getting larger increases[1] and some getting decreases.[54,55]

Nearly all studies to date published in the peer-reviewed literature agree that extreme precipitation event number and intensity have risen, when averaged over the United States. The pattern of change for the wettest day of the year is projected to roughly follow that of the average precipitation, with both increases and decreases across the U.S. Extreme hydrologic events are projected to increase over most of the U.S.

New information and remaining uncertainties

A key issue (uncertainty) is the ability of climate models to simulate precipitation. This is one of the more challenging aspects of modeling of the climate system because precipitation involves not only large-scale processes that are well-resolved by models but also small-scale process, such as convection, that must be parameterized in the current generation of global and regional climate models.

Viable avenues to improving the information base are to perform some long, very high-resolution simulations of this century's climate under different emissions scenarios.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, confidence is **high** that heavy downpours are increasing in most regions of the U.S., with especially large increases in the Midwest and Northeast.

Confidence is **high** that further increases in the frequency and intensity of extreme precipitation events are projected for most U.S. areas, given the evidence base and uncertainties.

Key message #7 Traceable Account

There have been changes in some types of extreme weather events over the last several decades. Heat waves have become more frequent and intense, especially in the West. Cold waves have become less frequent and intense across the nation. There have been regional trends in floods and droughts. Droughts in the Southwest and heat waves everywhere are projected to become more intense, and cold waves less intense everywhere.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Analysis of U.S. temperature records indicates that record cold events are becoming progressively less frequent relative to record high events.[60,170] There is evidence for the corresponding trends in a global framework.[7,66] A number of publications have explored the increasing trend of heat waves.[7,62,69] Additionally, heat waves observed in the southern Great Plains,[1] Europe,[7,62] and Russia[60,66,67] have now been shown to have a higher probability of having occurred because of human-induced climate change.

Some parts of the U.S. have been seeing changing trends for floods and droughts over the last 50 years, with some evidence for human influence.[13,48,62] In the areas of increased flooding in parts of the Great Plains, Midwest, and Northeast, increases in both total precipitation and extreme precipitation have been observed and may be contributing to the flooding increases. However, when averaging over the entire contiguous U.S., there is no overall trend in flood magnitudes.[71] A number of publications project drought as becoming a more normal condition over much of the southern and central U.S. (most recent references: Dai 2012; Hoerling et al. 2012; Wehner et al. 2011[75,76]).

Analyses of U.S. daily temperature records indicate that low records are being broken at a much smaller rate than high records, and at the smallest rate in the historical record.[60,170] However, in certain localized regions, natural variations can be as large or larger than the human induced change.

New information and remaining uncertainties

The key uncertainty regarding projections of future drought is how soil moisture responds to precipitation changes and potential evaporation increases. Most studies indicate that many parts of the U.S. will experience drier soil conditions but the amount of that drying is uncertain.

Natural variability is also an uncertainty affecting projections of extreme event occurrences in shorter timescales (several years to decades), but the changes due to human influence become larger relative to natural variability as the timescale lengthens. Stakeholders should view the occurrence of extreme events in the context of increasing probabilities due to climate change.

Continuation of long term temperature and precipitation observations is critical to monitoring trends in extreme weather events.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, confidence is **high** for the entire key message.

Heat waves have become more frequent and intense, and confidence is **high** that heat waves everywhere are projected to become more intense in the future.

Confidence is **high** that cold waves have become less frequent and intense across the nation.

Confidence is **high** that there have been regional trends in floods and droughts.

Confidence is **high** that droughts in the Southwest are projected to become more intense.

KEY MESSAGE #8 TRACEABLE ACCOUNT

The intensity, frequency, and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Category 4 and 5) hurricanes, have all increased since the early 1980s. The relative contributions of human and natural causes to these increases are still uncertain. Hurricane-associated storm intensity and rainfall rates are projected to increase as the climate continues to warm.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Recent studies suggest that the most intense Atlantic hurricanes have become stronger since the early 1980s.[93] While this is still the subject of active research, this trend is projected to continue.[90,91]

New information and remaining uncertainties

Detecting trends in Atlantic and eastern North Pacific hurricane activity is challenged by a lack of consistent historical data and limited understanding of all of the complex interactions between the atmosphere and ocean that influence hurricanes.[87,88]

While the best analyses to date[87,91] suggest an increase in intensity and in the number of the most intense hurricanes over this century, there remain significant uncertainties.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

High confidence that the intensity, frequency, and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Category 4 and 5) hurricanes, have increased substantially since the early 1980s.

Low confidence in relative contributions of human and natural causes in the increases.

Medium confidence that hurricane intensity and rainfall rates are projected to increase as the climate continues to warm.

KEY MESSAGE #9 TRACEABLE ACCOUNT

Winter storms have increased in frequency and intensity since the 1950s, and their tracks have shifted northward over the United States. Other trends in severe storms, including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds, are uncertain and are being studied intensively.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Current work[98] has provided evidence of the increase in frequency and intensity of winter storms, with the storm tracks shifting poleward,[99,100] but some areas have experienced a decrease in winter storm frequency.[1] Although there are some indications of increased blocking (a large-scale pressure pattern with little or no movement) of the wintertime circulation of the Northern Hemisphere,[106] the assessment and attribution of trends in blocking remain an active research area.[107] Some recent research has provided insight into the connection of global warming to tornadoes and severe thunderstorms.[96]

New information and remaining uncertainties

Winter storms and other types of severe storms have greater uncertainties in their recent trends and projections, compared to hurricanes (Key Message 8). The text for this key message explicitly acknowledges the state of knowledge, pointing out "what we don't know." There has been a sizeable upward trend in the number of storm events causing large financial and other losses.[95]

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

Confidence is **medium** that winter storms have increased slightly in frequency and intensity, and that their tracks have shifted northward over the U.S.

Confidence is **low** on other trends in severe storms, including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds.

Key message #10 Traceable Account

Global sea level has risen by about 8 inches since reliable record keeping began in 1880. It is projected to rise another 1 to 4 feet by 2100.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

Nearly all studies to date published in the peer-reviewed literature agree that global sea level has risen during the past century, and that it will continue to rise over the next century.

Tide gauges throughout the world have documented rising sea levels during the last 130 years. This rise has been further confirmed over the past 20 years by satellite observations, which are highly accurate and have nearly global coverage. Recent studies have shown current sea level rise rates are increasing[112,123] and project that future sea level rise over the rest of this century will be faster than that of the last 100 years (Appendix 3: Climate Science, Supplemental Message 12).[123]

New information and remaining uncertainties

The key issue in predicting future rates of global sea level rise is to understand and predict how ice sheets in Greenland and Antarctica will react to a warming climate. Current projections of global sea level rise do not account for the complicated behavior of these giant ice slabs as they interact with the atmosphere, the ocean and the land. Lack of knowledge about the ice sheets and their behavior is the primary reason that projections of global sea level rise includes such a wide range of plausible future conditions.

Early efforts at semi-empirical models suggested much higher rates of sea level rise (as much as 6 feet by 2100).[115,117] More recent work suggests that a high end of 3 to 4 feet is more plausible.[115,116,121] It is not clear, however, whether these statistical relationships will hold in the future or that they are appropriate in modeling past behavior, thus calling their reliability into question.[118] Some decision-makers may wish to consider a broader range of scenarios such as 8 inches or 6.6 feet by 2100 in the context of risk-based analysis.[122,123]

Assessment of confidence based on evidence

Given the evidence and uncertainties, confidence is **very high** that global sea level has risen during the past century, and that it will continue to rise over this century, with **medium** confidence that global sea level rise will be in the range of 1 to 4 feet by 2100.

Key message #11 Traceable Account

Rising temperatures are reducing ice volume and surface extent on land, lakes, and sea. This loss of ice is expected to continue. The Arctic Ocean is expected to become essentially ice free in summer before mid-century.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

There have been a number of publications reporting decreases in ice on land[147] and glacier recession. Evidence that winter lake ice and summer sea ice are rapidly declining is based on satellite data and is incontrovertible.[111,172]

Nearly all studies to date published in the peer-reviewed literature agree that summer Arctic sea ice extent is rapidly declining,[131] with even greater reductions in ice thickness[132,133] and volume,[134] and that if heat-trapping gas concentrations continue to rise, an essentially ice-free Arctic ocean will be realized sometime during this century (for example, Stroeve et al. 2012[136]). September 2012 had the lowest levels of Arctic ice in recorded history. Great Lakes ice should follow a similar trajectory. Glaciers will generally retreat, except for a small percentage of glaciers that experience dynamical surging.[111] Snow cover on land has decreased over the past several decades.[145] The rate of permafrost degradation is complicated by changes in snow cover and vegetation.

New information and remaining uncertainties

The rate of sea ice loss through this century is a key issue (uncertainty), which stems from a combination of large differences in projections between different climate models, natural climate variability and uncertainty about future rates of fossil fuel emissions. This uncertainty is illustrated in Figure 2.29, showing the CMIP5-based projections (adapted from Stroeve et al. 2012[136]).

Viable avenues to improving the information base are determining the primary causes of the range of different climate model projections and determining which climate models exhibit the best ability to reproduce the observed rate of sea-ice loss.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, confidence is **very high** that rising temperatures are reducing ice volume and extent on land, lakes, and sea, and that this loss of ice is expected to continue.

Confidence is **very high** that the Arctic Ocean is projected to become virtually ice-free in summer by mid-century.

KEY MESSAGE #12 TRACEABLE ACCOUNT

The oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually and are becoming more acidic as a result, leading to concerns about intensifying impacts on marine ecosystems.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input.

The oceans currently absorb a quarter of the CO_2 the caused by human activities.[155] Publications have shown that this absorption causes the ocean to become more acidic (for example, Doney et al. 2009[154]). Recent publications demonstrate the adverse effects further acidification will have on marine life.[158,165,169]

New information and remaining uncertainties

Absorption of CO_2 of human origin, reduced pH, and lower calcium carbonate ($CaCO_3$) saturation in surface waters, where the bulk of oceanic production occurs, are well verified from models, hydrographic surveys, and time series data.[158] The key issue (uncertainty) is how future levels of ocean acidity will affect marine ecosystems.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, confidence is **very high** that oceans are absorbing about a quarter of emitted CO_2.

Very high for trend of ocean acidification; **low-to-medium** for intensifying impacts on marine ecosystems. Our present understanding of projected ocean acidification impacts on marine organisms stems largely from short-term laboratory and mesocosm experiments, although there are also examples based on actual ocean observations; consequently, the response of individual organisms, populations, and communities of species to more realistic, gradual changes still has large uncertainties.