2. Our Changing Climate

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Key Messages

1. **Global climate is changing now and this change is apparent across a wide range of observations. Much of the climate change 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 climate is to those emissions.**
3. **U.S. average temperature has increased by about 1.5°F since record keeping began in 1895; more than 80% of this increase has occurred since 1980. The most recent decade was the nation's warmest on record. U.S. temperatures 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, 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 U.S., affecting ecosystems and agriculture. Continued lengthening of the growing season across the U.S. is projected.

5. **Precipitation averaged over the entire U.S. has increased during the period since 1900, but regionally some areas have had increases greater than the national average, and some areas have had decreases. The largest increases have been in the Midwest, southern Great Plains, and Northeast. Portions of the Southeast, the Southwest, and the Rocky Mountain states have experienced decreases. More winter and spring precipitation is projected for the northern U.S., and less for the Southwest, over this century.**
6. **Heavy downpours are increasing in most regions of the U.S., especially over the last three to five decades. Largest increases are in the Midwest and Northeast. Further increases in the frequency and intensity of extreme precipitation events are projected for most U.S. areas.**
7. **Certain types of extreme weather events have become more frequent and intense, including heat waves, floods, and droughts in some regions. The increased intensity of heat waves has been most prevalent in the western parts of the country, while the intensity of flooding events has been more prevalent over the eastern parts. Droughts in the Southwest and heat waves everywhere are projected to become more intense in the future.**
8. **There has been an increase in the overall strength of hurricanes and in the number of strong (Category 4 and 5) hurricanes in the North Atlantic since the early 1980s. The intensity of the strongest hurricanes is projected to continue to increase as the oceans continue to warm; ocean cycles will also affect the amount of warming at any given time. With regard to other types of storms that affect the U.S., winter storms have increased slightly in frequency and intensity, and their tracks have shifted northward over the U.S. Other trends in severe storms, including the numbers of hurricanes and the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds are uncertain and are being studied intensively.**
9. **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.**
10. **Rising temperatures are reducing ice volume and extent on land, lakes, and sea. This loss of ice is expected to continue.**
11. **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 potential impacts on marine ecosystems.**

Our Changing Climate

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 requires a broader geographical perspective in some parts of the discussion. Additional geographic detail is presented in the regional chapters of this report. Further details on the topics of this chapter are provided in the Appendix.

Since the previous national climate assessment was published in 2009, the climate has continued to change, with resulting effects on the U.S. 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 below.

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.
- 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. 2012 has set a new record for minimum area of Arctic ice.
- 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 of potential increases over this century.
- New approaches to building scenarios of the future have allowed for investigations of the implications of deliberate reductions in heat-trapping gas emissions.

Eleven key messages are presented below, together with supporting evidence. The discussion of each key message begins with a summary of recent variations or trends, followed by information on the corresponding changes projected for the future.

Observed Climate Change

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

Many aspects of the global climate are changing rapidly, and the primary drivers of that change are human in origin. Evidence for climate change abounds, from the top of the atmosphere to the depths of the oceans (Kennedy et al. 2010). This evidence has been painstakingly compiled by scientists and engineers from around the world using satellites, weather balloons, thermometers at surface stations, and many other types of observing systems that monitor the Earth's climate system. The sum total of this evidence tells an unambiguous story: the planet is warming. Temperatures at the surface, in the troposphere (the active weather layer extending up to about 8 to 12 miles above the ground), and in the oceans have all increased over recent decades. Snow and ice cover have decreased in most areas. Atmospheric water vapor due to increased evaporation from the warmer surface has been increasing in the lower atmosphere, as have sea levels. 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 trends in extremes of heat, cold, drought, and heavy precipitation events (Alexander et al. 2006).

Climate model simulations reinforce scientific understanding that observed variations in global average surface temperature over the past century can only be explained through a combination of human and natural factors. However, 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 (Gillett et al. 2012). Natural variability, including the effects of El Niño and La Niña events and various ocean cycles, also affects climate, but the changes observed over the past 50 years are far larger than natural variability can account for. The majority of the warming can only be explained by the effects of human influences (Gillett et al. 2012; Stott et al. 2010), especially the emissions from burning of fossil fuels such as coal, oil, and natural gas. This robust scientific attribution of observed changes to human influence extends to many other climate quantities, such as precipitation (Min et al. 2011; Pall et al. 2011), humidity (Santer et al. 2007; Willett et al. 2007), pressure (Gillett and Stott 2009), ocean heat content (AchutaRao et al. 2006), and tropospheric and stratospheric temperature (Santer et al. 2012) in addition to surface temperature. Further discussion of attribution is provided in the Appendix.

Natural variations in climate include the effects of the natural cycles mentioned above, plus the 11-year sunspot cycle and other changes in the radiation from the Sun, as well as the effects of volcanic eruptions. Natural variations can be as large as human-induced climate change over timescales of up to a decade or two at the global scale. As a result, global temperature does not always increase steadily, as evidenced, for example, by the period between 1998 and 2007, which showed little change. 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 (Easterling and Wehner 2009; Foster and Rahmstorf 2011; Knight et al. 2009; Rahmstorf et al. 2012; Santer et al. 2011). Over the time scale of multiple decades, the human influence has been dominant, and the most recent 10-year period is clearly the hottest on record. Note that changes in temperature at local scales, such as urban areas, can be quite different than those at larger spatial scales, in part because of local land-use patterns.

Box: Models Used in the Assessment

Throughout the 2013 National Climate Assessment report, there are references to projections from models of the physical processes affecting the Earth's climate system. Three distinct sets of model simulations are discussed:

- Climate Model Intercomparison Project, 3rd phase (CMIP3): global model analyses done for the 2007 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 assessments included in this report.
- Climate Model Intercomparison Project, 5th phase (CMIP5): Newer global model analyses done for the 2013 IPCC assessment. 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 for it to serve as the foundation for the impacts assessments in this report, and information from CMIP5 is primarily provided for comparison purposes.
- North American Regional Climate Change Assessment Program (NARCCAP): 6 regional climate model analyses (and one global model) for the continental U.S. run at about 30-mile horizontal resolution.

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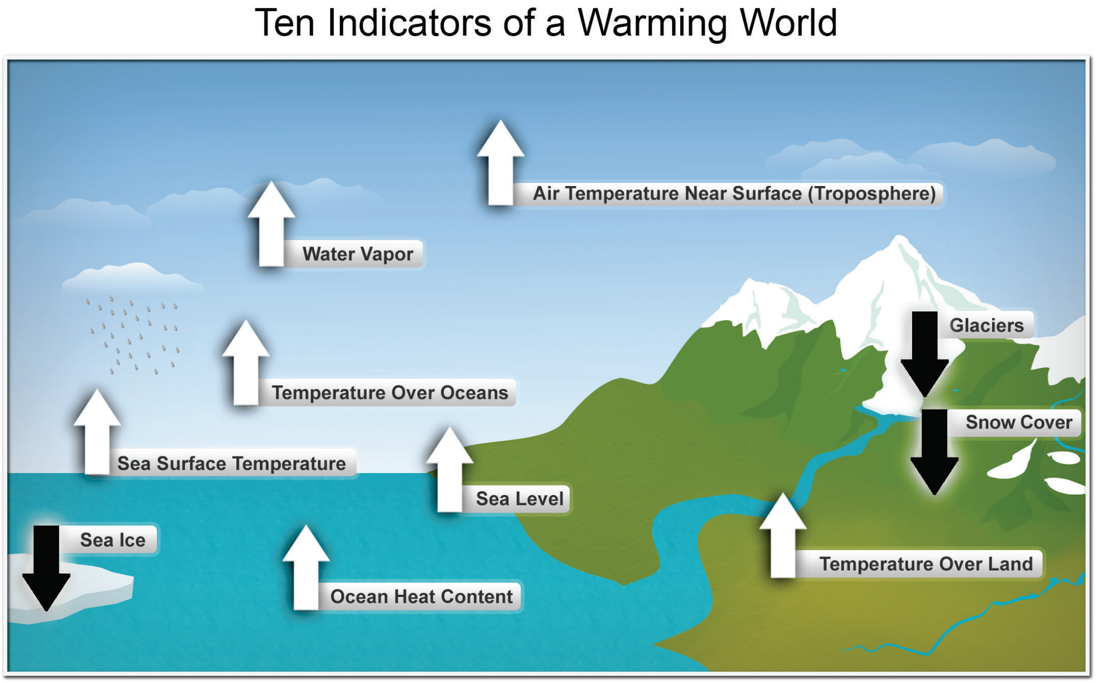

Figure 2.1: Ten Indicators of a Warming World

Caption: These are just some of the many indicators that have been measured globally over many decades and that show that Earth's climate is warming. White arrows indicate increasing trends, black arrows indicate decreasing trends. All the indicators expected to increase in a warming world are increasing, and all those expected to decrease in a warming world are decreasing. (Figure source: NOAA NCDC)

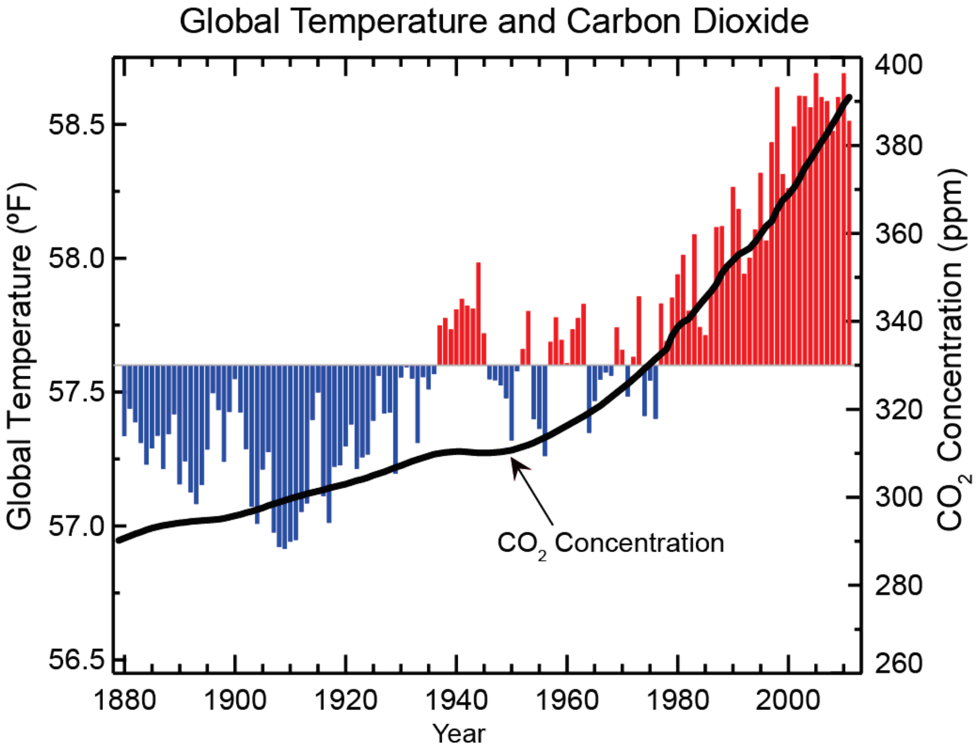

Figure 2.2: Global Temperature and Carbon Dioxide

Caption: Global annual average temperature (as measured over both land and oceans; scale on left) has increased by more than 1.4°F (0.8°C) since 1880. 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); scale on right. 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 the eruption of large volcanoes. (Figure source: NOAA NCDC. Temperature data from NOAA NCDC 2012; CO2 data from NOAA ESRL 2012.)

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 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 occur even if all emissions from human activities were suddenly stopped (Matthews and Zickfeld 2012). 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 many aspects of human society and the natural world.

Our 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 (Taylor et al. 2012) used in the IPCC's current assessment versus those in the previous assessment (IPCC 2007) 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 reduction designed to limit the global temperature increase to 3.6°F (2°C) above pre-industrial levels (Schnellnhuber et al. 2006). This path would require emission reductions (more than 70% reduction in human-related emissions by 2050 – see Appendix, Key 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, and aggressive reductions in heat-trapping gas emissions.

Projections of changes in precipitation largely follow recently observed patterns of change, with overall 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 belt that lies just outside the tropics (greater than 23°N/S) expands further poleward and receives 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 (Karl et al. 2009)) and the Mediterranean, are already dry and are expected to become drier. The widespread trend toward more heavy downpours is expected to continue, with precipitation becoming less frequent but more intense. 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 resolution of global climate models is typically about 60 miles.

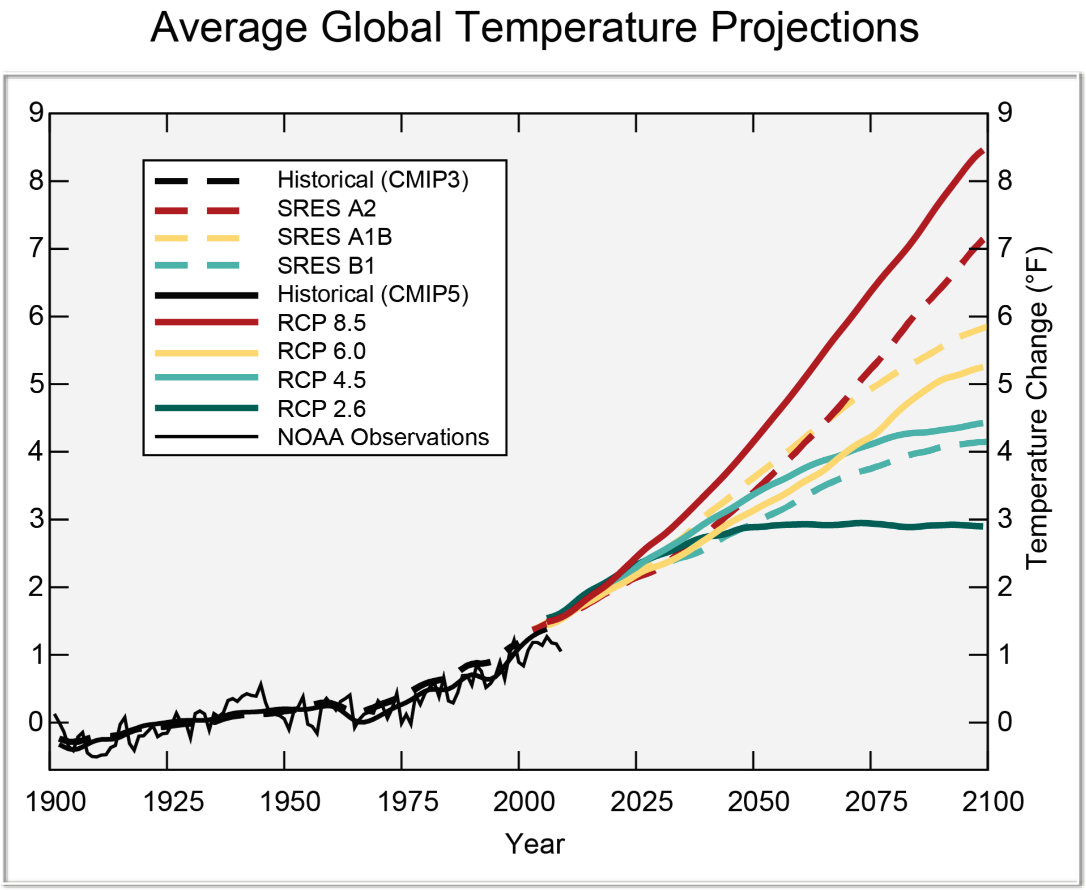

Figure 2.3: Average Global Temperature Projections

Caption: Projected global average annual temperature changes (°F) for multiple future emissions scenarios relative to the 1901-1960 average temperature. The dashed lines are results from the previous generation of climate models using the previous generation of emissions scenarios (the SRES set). The solid lines are results from the most recent generation of climate models using the most recent emissions scenarios (the RCP set), some of which consider explicit climate policies, which the older ones did not. Differences among these projections are principally a result of differences in the emissions scenarios rather than differences among the climate models. (Figure source: Michael Wehner, LBNL. Data from CMIP3, CMIP5, and NOAA, 2012.)

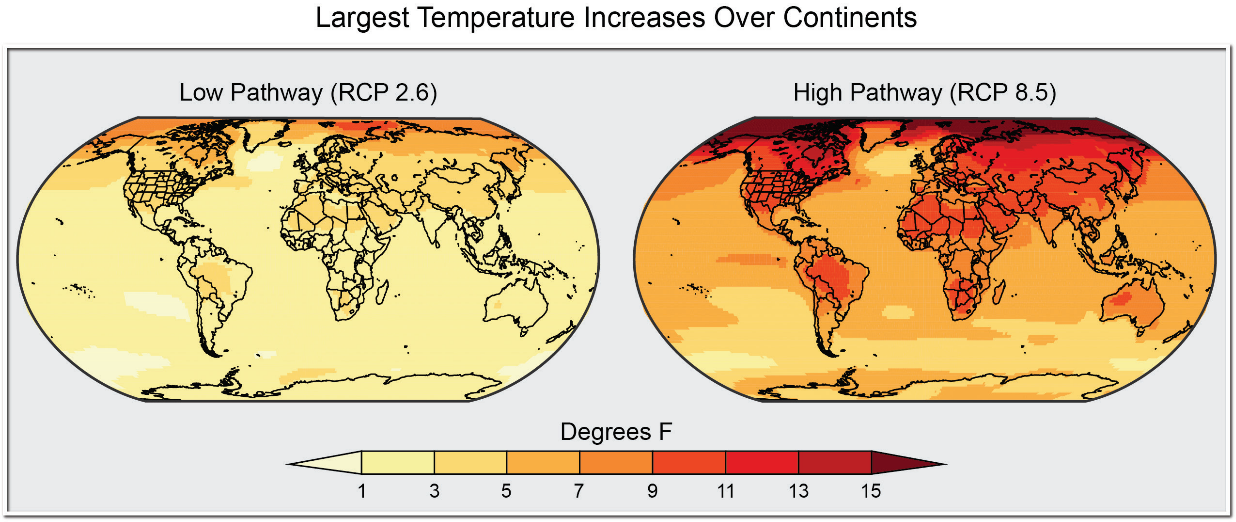

Figure 2.4: Largest Temperature Increases Over Continents

Caption: Projected change (°F) in annual average temperature over the period 2071-2099 (compared to the period 1971-2000) under a low emissions pathway (RCP 2.6, left graph) that assumes rapid reductions in emissions and a high pathway (RCP 8.5, right graph) that assumes continued increases in emissions. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP5.)

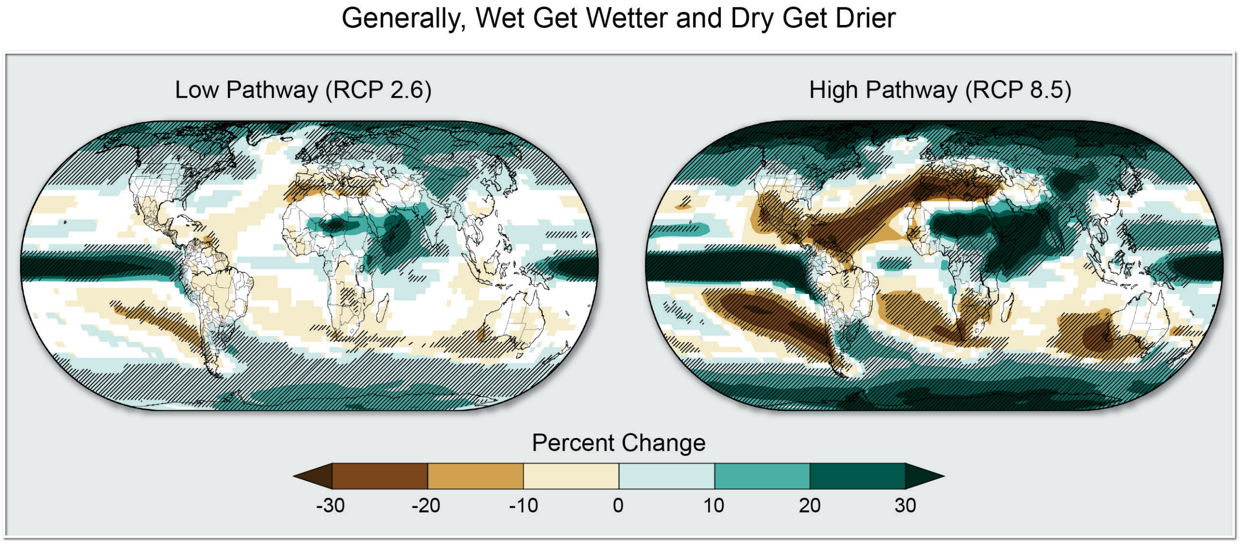

Figure 2.5: Generally, Wet Get Wetter and Dry Get Drier

Caption: Projected percent change in annual average precipitation over the period 2071-2099 (compared to the period 1901-1960) under a low emissions pathway (RCP 2.6) that assumes rapid reductions in emissions and a high pathway (RCP 8.5) that assumes continued increases in emissions. Teal indicates precipitation increases, and brown, decreases. Hatched areas indicate confidence that the projected changes are large and are consistently wetter or drier. White areas indicate confidence that the changes are small. Wet regions generally tend to become wetter while dry regions become drier. In general, the northern parts of the U.S. (especially the Northeast and Alaska) are projected to see more precipitation, while the southern part (especially the Southwest) is projected to see less. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP5, analyzed by Michael Wehner, LBNL.) *(note: to be redone with base period 1971-2000)*

Recent U.S. Temperature Trends

U.S. average temperature has increased by about 1.5°F since record keeping began in 1895; more than 80% of this increase has occurred since 1980. The most recent decade was the nation's warmest on record. U.S. temperatures 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, 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 (Fall et al. 2010; Fall et al. 2011; Karl et al. 2009; Menne and Williams Jr 2009; Menne et al. 2009; Menne et al. 2010; Vose et al. 2012; Williams et al. 2012) (Appendix, Key Message 6 for more information). These advances, together with the continued warming, have strengthened our confidence in, and understanding of the reasons for, the warming. They also confirm that the average annual temperatures have increased over most of the U.S. by about 1.5°F since 1895 (Menne et al. 2009). However, this increase was not constant over time. In particular, temperatures generally rose until about 1940, declined until about 1980, then increased rapidly thereafter, with 80% of the total increase occurring after 1980. Over even shorter time scales up to a decade or more, natural variability (see the Appendix) can reduce the rate of warming or even create a temporary cooling. The cooling in mid-century that was especially prevalent over the eastern half of the U.S. may also have stemmed partly from the cooling effects of sulfate particles from coal burning power plants (Leibensperger et al. 2012), before these sulfur emissions were regulated to address health and acid rain concerns.

Since 1991, temperatures have averaged 1°F to 1.5°F higher than 1901-1960 over most of the U.S., 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.

The cooling in mid-century extended over most of the southern and eastern U.S., and temperatures decreased slightly in parts of the Southeast if measured as a trend over the full century 1900-2000 (in contrast to almost all other global land areas, which warmed over that period). Such regional cooling can occur occasionally because natural variations can be larger than human influences over small areas for periods of decades. However, the Southeast has warmed over the past few decades and 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.

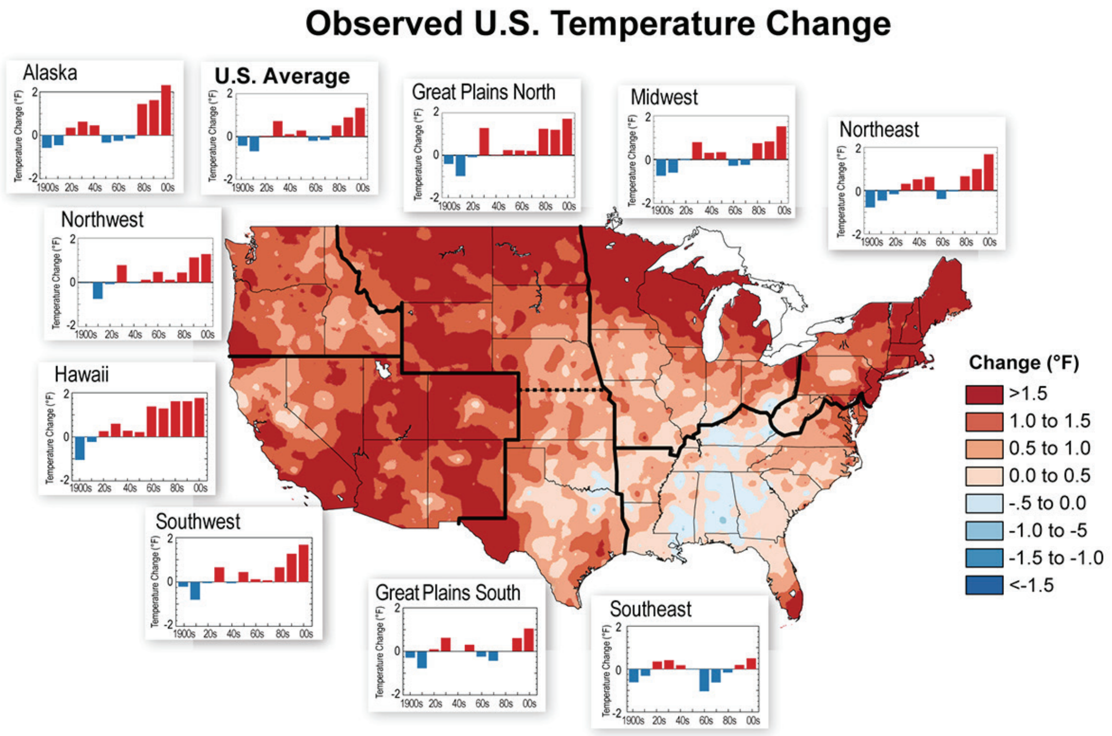

Figure 2.6: Observed U.S. Temperature Change

Caption: The colors on the map show temperature changes over the past 20 years in °F (1991-2011) compared to the 1901-1960 average. The bars on the graphs show the average temperature changes by decade for 1901-2011 (relative to the 1901-1960 average) for each region. The far right bar in each graph (2000s decade) includes 2011. The period from 2001 to 2011 was warmer than any previous decade in every region. (Figure source: NOAA NCDC / CICS-NC. Data from NOAA NCDC.)

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 of emissions of those gases. The amount of warming over the next few decades is projected to be similar regardless of emissions scenario. 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 future emissions, 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.

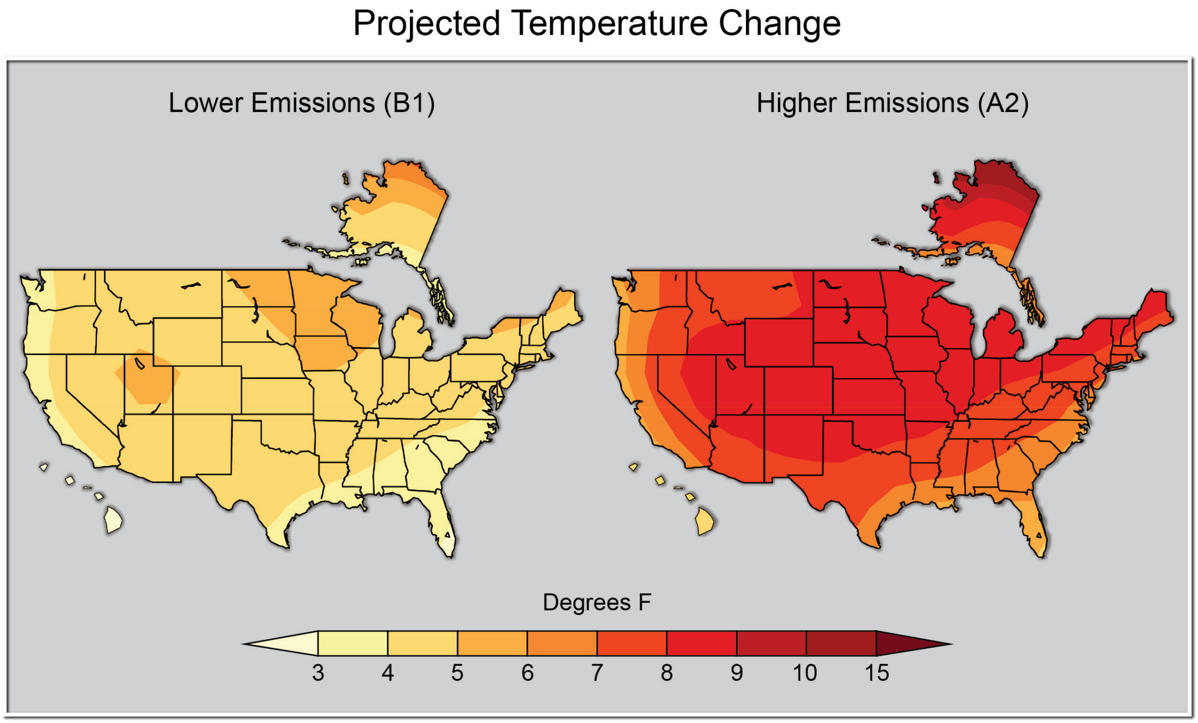

Figure 2.7: Projected Temperature Change

Caption: Maps show projected change in average surface air temperature in the later part of this century (2070-2099) relative to the later part of the last century (1971-1999) 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). These scenarios are used throughout this report for assessing impacts under lower and higher emissions. Projected changes are averages from 15 CMIP3 models for the A2 scenario and 14 models for the B1 scenario. (See Appendix, Key Message 5 for a discussion of temperature changes under a wider range of future scenarios for various periods of this century). (Figure source: adapted from (Kunkel et al. 2012).)

BOX: Newer Simulations for Projected Temperature (CMIP5 models)

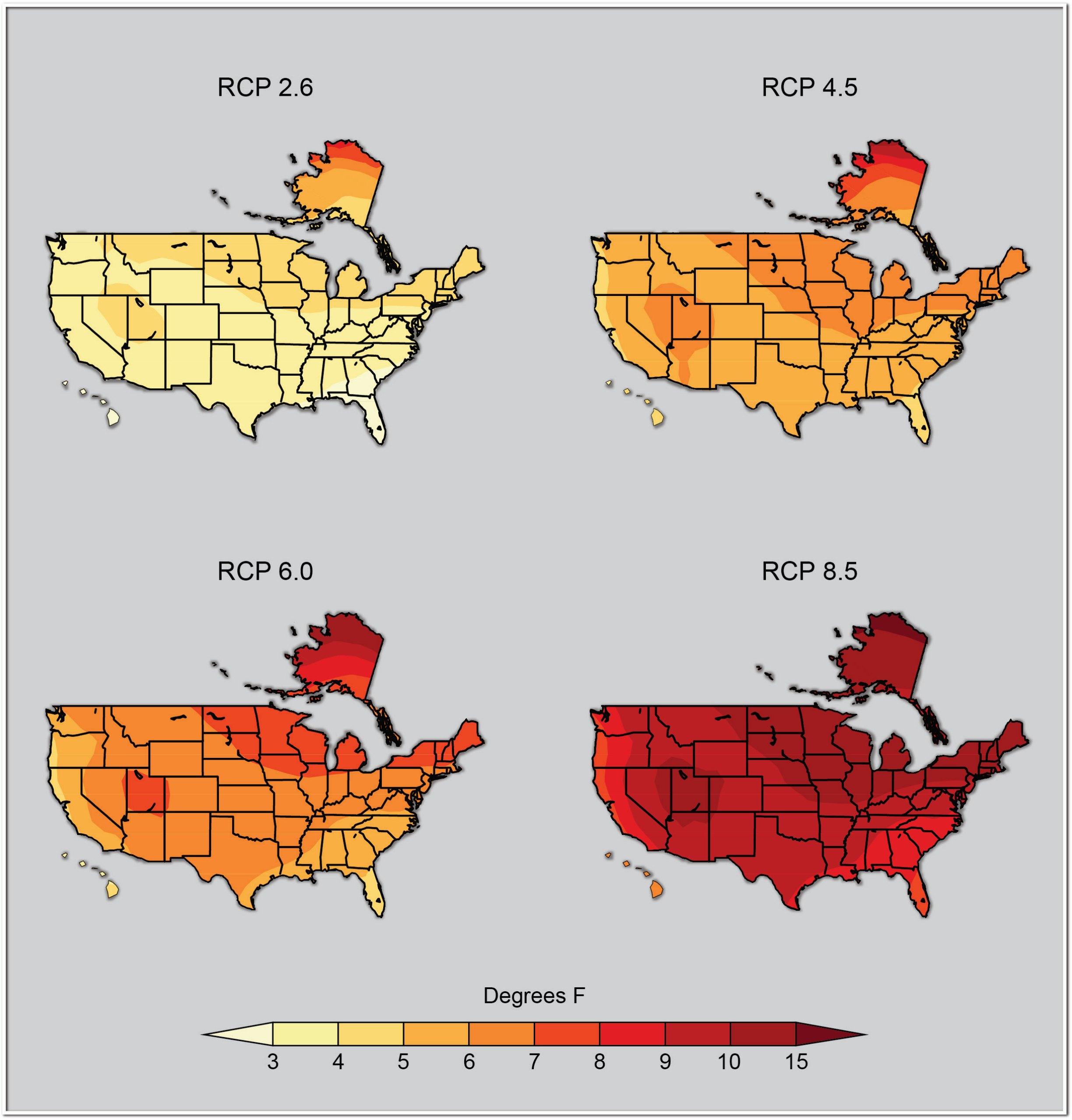

Figure 2.8:

Caption: The largest uncertainty in projecting future climate change is the level of emissions. The most recent model projections (shown above) take into account a wider range of options with regard to human behavior; these include a lower emissions scenario (RCP 2.6, top left) than has been considered before. This scenario assumes rapid reductions in emissions – more than 70% cuts from current levels by 2050 – and the corresponding smaller amount of warming. On the high end, they include a scenario that assumes continued increases in emissions (RCP 8.5, bottom right) and the corresponding greater amount of warming. Also shown are temperature changes (°F) for the intermediate scenarios RCP 4.5 (top right, which is most similar to B1) and RCP 6.0 (bottom left, which is most similar to A1B; see the Appendix). Projections show change in average surface air temperature in the later part of this century (2071-2099) relative to the late part of the last century (1971-2000). (Figure source: NOAA NCDC / CICS-NC. Data from CMIP5.)

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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 U.S., affecting ecosystems and agriculture. Continued lengthening of the growing season across the U.S. is projected.

The length of the frost-free season (or growing season, in common usage) is a major determinant of the types of plants and crops that are well-adapted to a particular region. The frost-free season length has been gradually increasing since the 1980s (U.S. Environmental Protection Agency 2010). 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 (Dragoni et al. 2011), satellite estimates of the length of the growing season (Jeong et al. 2011), and length of the ragweed pollen season (Ziska et al. 2011). A longer growing season can mean greater evaporation and loss of moisture through plant transpiration associated with higher temperatures so that even with a longer frost-free season, crops could be negatively affected by drying. Likewise, increases in forest productivity can be offset by drying, leading to an earlier and longer fire season and more intense fires.

The lengthening of the frost-free season has been somewhat greater in the western U.S. than the eastern U.S. (Karl et al. 2009), 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.

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, consistent with rising sea surface temperatures. The increases would 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 north, with increasing frequencies of years without subfreezing temperatures in the most southern parts of the U.S.

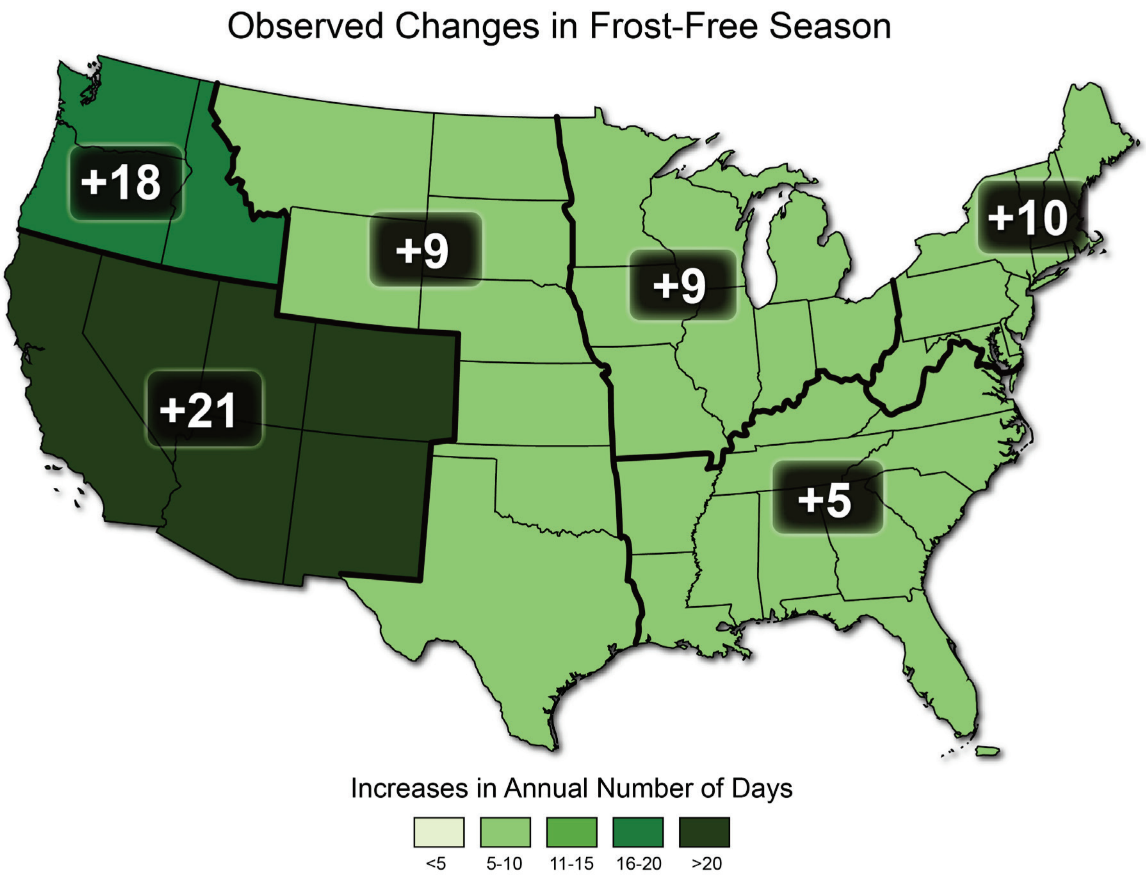

Figure 2.9: Observed Changes in Frost-Free Season

Caption: 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 1991-2011 relative to 1901-1960. Increases in frost-free days correspond to similar increases in growing season length. (Figure source: NOAA/NCDC / CICS-NC. Data from Kunkel et al. 2012a, 2012b, 2012c, 2012d, 2012e, 2012f).

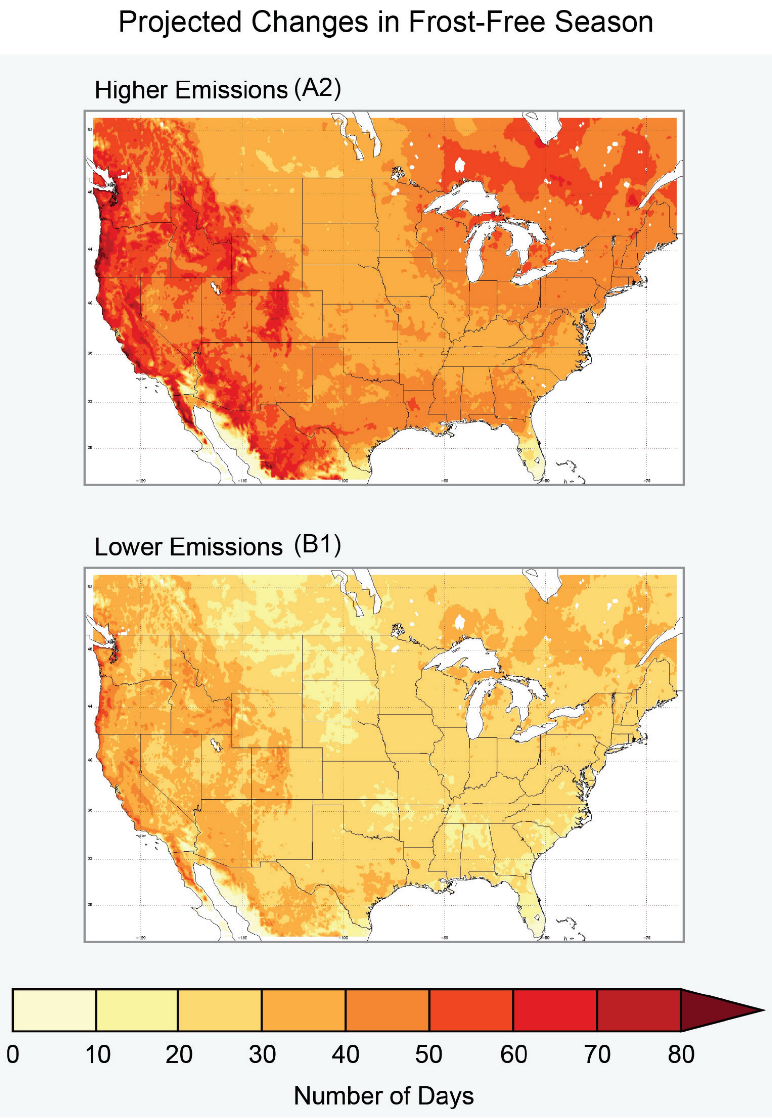

Figure 2.10: Projected Changes in Frost-Free Season

Caption: The maps show projected increases in frost-free days 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, top map) and one in which emissions are rapidly reduced (B1, bottom map). Increases in the frost-free season correspond to similar increases in the growing season. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP3 Daily Statistically Downscaled; Hayhoe et al. 2008; Hayhoe et al. 2004; Kunkel et al. 2012)

U.S. Precipitation Change

Precipitation averaged over the entire U.S. has increased during the period since 1900, but regionally some areas have had increases greater than the national average, and some areas have had decreases. The largest increases have been in the Midwest, southern Great Plains, and Northeast. Portions of the Southeast, the Southwest, and the Rocky Mountain states have experienced decreases. More winter and spring precipitation is projected for the northern U.S., 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 (McRoberts and Nielsen-Gammon 2011; Peterson et al. 2012).

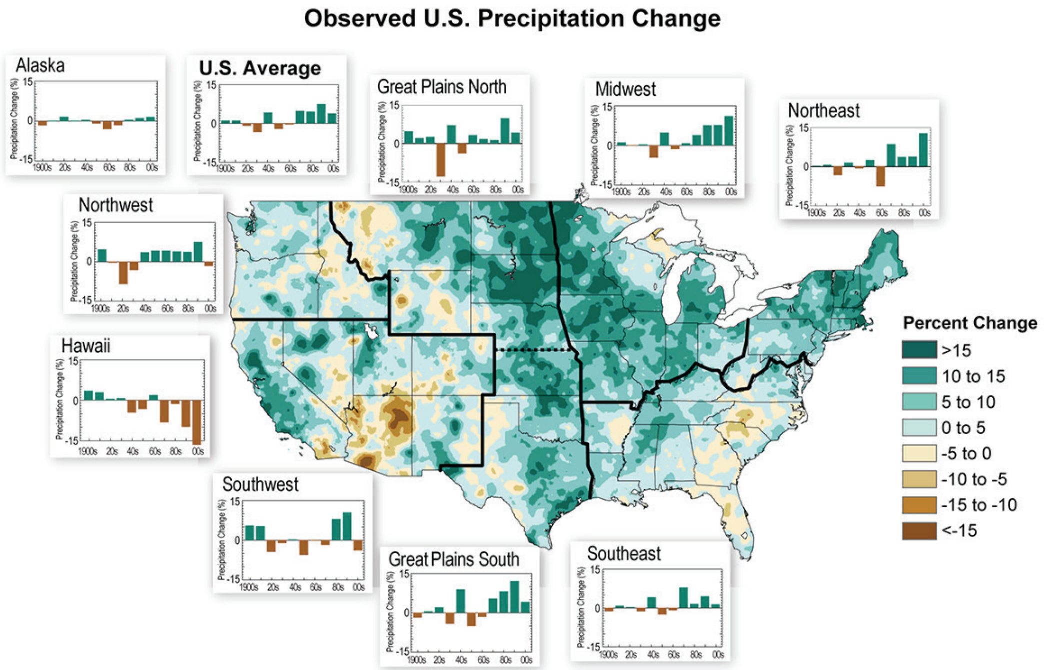

Figure 2.11: Observed U.S. Precipitation Change

Caption: The colors on the map show annual total precipitation changes (percent) for 1991-2011 compared to the 1901-1960 average, and show wetter conditions in most areas (McRoberts and Nielsen-Gammon 2011). The bars on the graphs show average precipitation differences by decade for 1901-2011 (relative to the 1901-1960 average) for each region. The far right bar is for 2001-2011. (Figure source: NOAA NCDC / CICS-NC. Data from NOAA NCDC.)

While significant trends in average precipitation have been detected, the fraction of these trends attributable to human activity is difficult to quantify because the range of natural variability in precipitation is large. However, if emissions of heat-trapping gases continue their upward trend, clear patterns of precipitation change are projected to emerge. 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 projected changes in the northern U.S. are a consequence of both a warmer atmosphere and associated large-scale circulation changes. Warmer air can hold more moisture than colder air, leading to more intense rainfall. The projected reduction in Southwest precipitation is a result of large-scale circulation changes caused by increased heating of the global atmosphere. Recent improvements in the understanding of these mechanisms of change increase confidence in these projections (Held and Soden, 2008). 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) natural variations can not be projected far into the future; and 2) current climate models are 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 the small details.

Projected Precipitation Change by Season

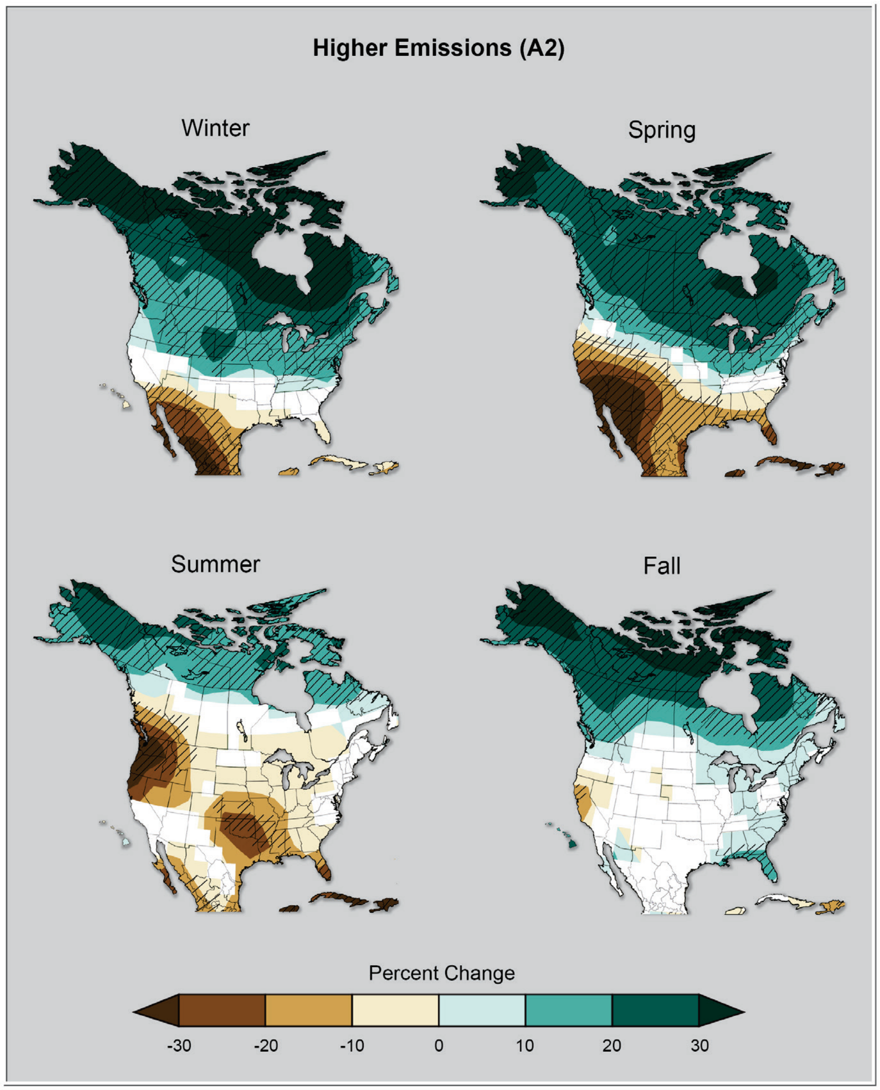

Figure 2.12: Projected Precipitation Change by Season

Caption: Projected percent change in seasonal precipitation for 2070-2099 (compared to the period 1901-1960) under an emissions scenario that assumes continued increases in emissions (A2). Teal indicates precipitation increases, and brown, decreases. Hatched areas indicate confidence that the projected changes are large and are consistently wetter or drier. White areas indicate confidence that the changes are small. Wet regions tend to become wetter while dry regions become drier. In general, the northern part of the U.S. is projected to see more winter and spring precipitation, while the Southwest is projected to experience less precipitation in the spring. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP3; analyzed by Michael Wehner, LBNL.) *(note: to be redone with base period 1971-2000)*

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 across the U.S. These include the global models used in the Coupled Model Intercomparison Project, versions 3 and 5 (CMIP3, CMIP5) as well as the suite of regional models (from the North American Regional Climate Change Assessment Program, NARCCAP). 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, but the regional suite generally shows conditions that are overall somewhat wetter 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 suite for the U.S. appear to arise partially or wholly from the choice of the four global climate models used to drive the regional simulations. These four models, averaged together, project average changes that are slightly (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 emissions 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 the winter and spring. Drier conditions in the summer are projected 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.

BOX: Newer Simulations for Projected Precipitation Change (CMIP5 models)

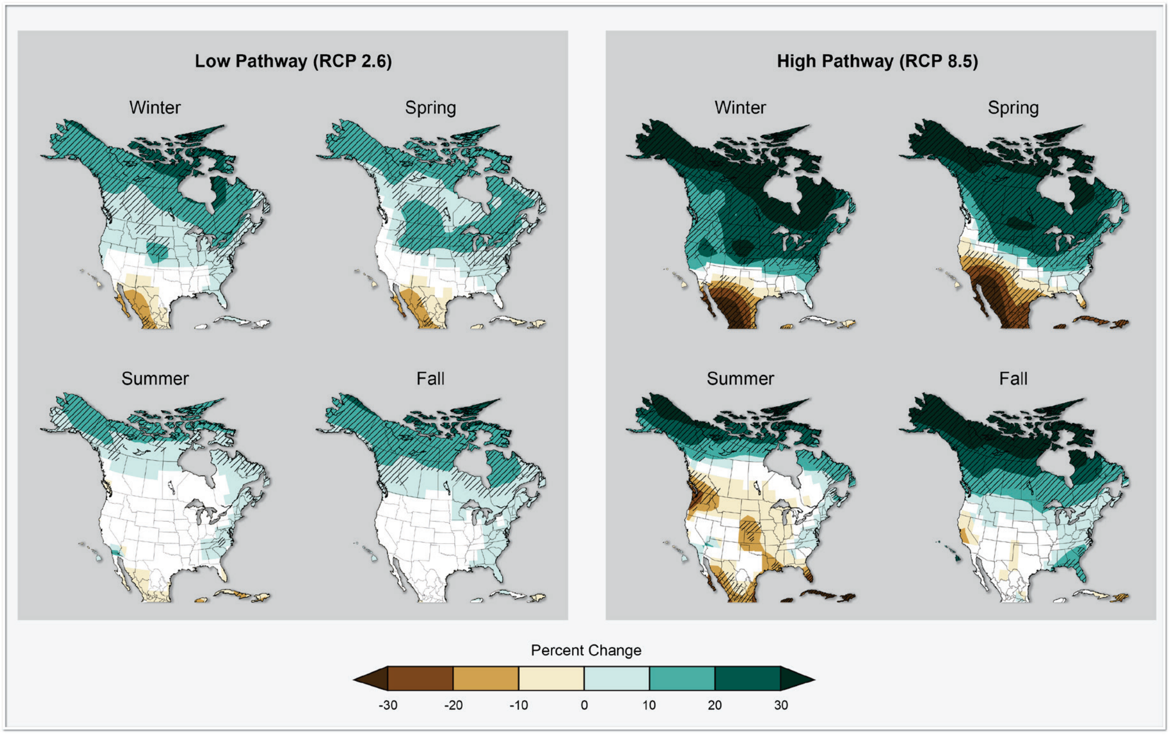

Figure 2.13

Projected seasonal precipitation change (percent) for 2071-2099 (compared to 1901-1960) as projected by recent simulations that include a wider range of emissions 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 could be expected to yield the more modest changes in the maps on the left. In these seasonal projections, teal indicates precipitation increases, and brown, decreases. Hatched areas indicate confidence that the projected changes are large and are consistently wetter or drier. White areas indicate confidence that the changes are small. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP5; analyzed by Michael Wehner, LBNL.) *(note: to be redone with base period 1971-2000)*

-- end box --

Heavy Downpours Increasing

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

Across most of the U.S., 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 above average in every region of the country, except Hawaii. This increase has been greatest in the Northeast, Midwest, and Great Plains – more than 30% above the 1901-1960 average (Karl et al. 2009). There has also been an increase in flooding events in the Midwest and Northeast where the largest increases in heavy rain amounts have occurred.

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 (Dai 2006; Simmons et al. 2010; Willett et al. 2008). 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 (Kunkel et al. 2012h).

Projections of future climate over the U.S. suggest that the recent trend towards a greater percentage of precipitation falling in heavy rain events will continue. In regions of increasing precipitation, such as the northern U.S., increasingly large percentages of the total precipitation will come from heavy downpours. In these areas, heavy-precipitation events that are presently rare will become more common in the future. Moreover, heavy downpours will account for increasingly large portions of the total precipitation in regions such as the Southwest, where total precipitation is projected to decrease (Kunkel et al. 2012h; Wehner 2012; Wuebbles et al. 2012).

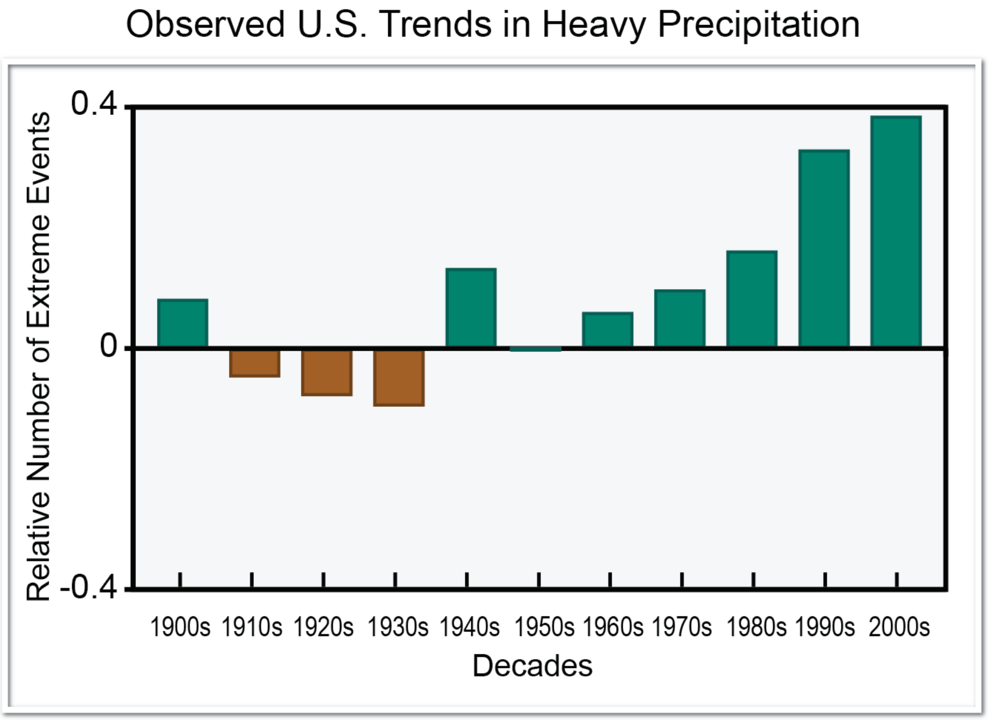

Figure 2.14: Observed U.S. Trends in Heavy Precipitation

Caption: 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 the once-in-five-year event. As this extreme precipitation index for 1901-2011 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 Hawaii. The 2000s decade (far right bar) includes 2001-2011. (Figure source: adapted from (Kunkel et al. 2012)

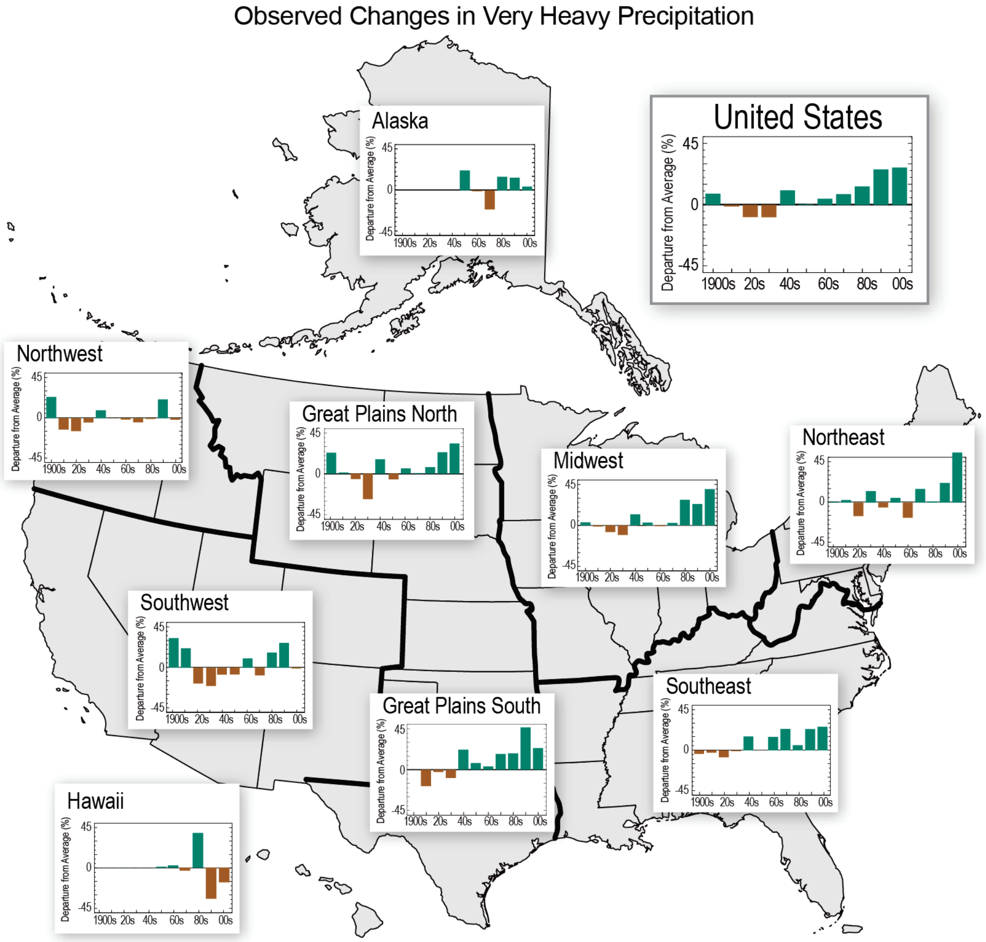

Figure 2.15: Observed Changes in Very Heavy Precipitation

Caption: 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 2011 for each region. The far right bar is for 2001-2011. In recent decades there have been increases everywhere, except for the Southwest, Northwest, and Hawaii, 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 Hawaii, which are relative to the 1951-1980 average. (Figure source: NOAA NCDC / CICS-NC)

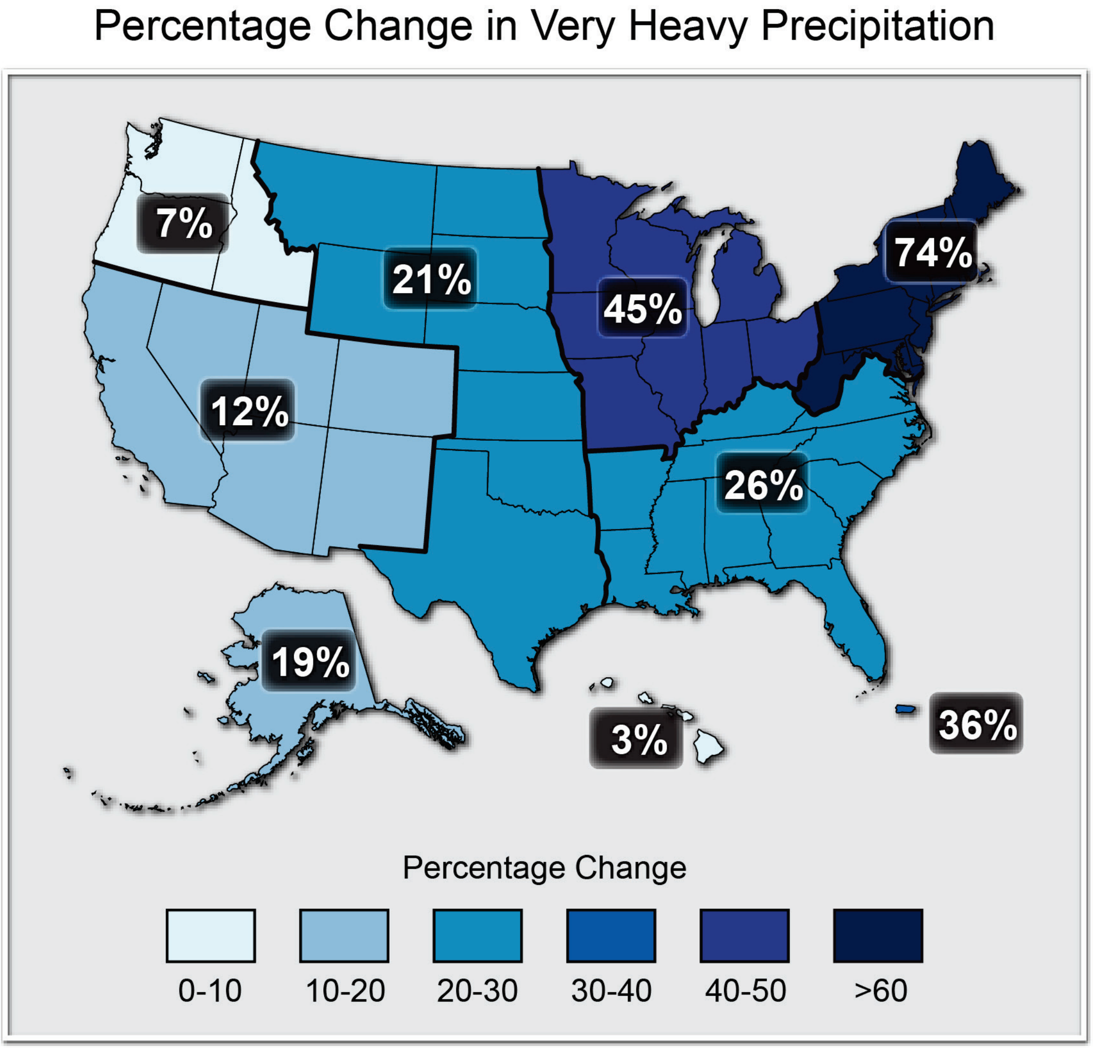

Figure 2.16: Percentage Change in Very Heavy Precipitation

Caption: 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 2011 for each region. There are clear trends toward a greater amount of *very heavy* precipitation for the nation as a whole, and particularly in the Northeast and Midwest. (Figure source: updated from (Karl et al. 2009) with data from NCDC)

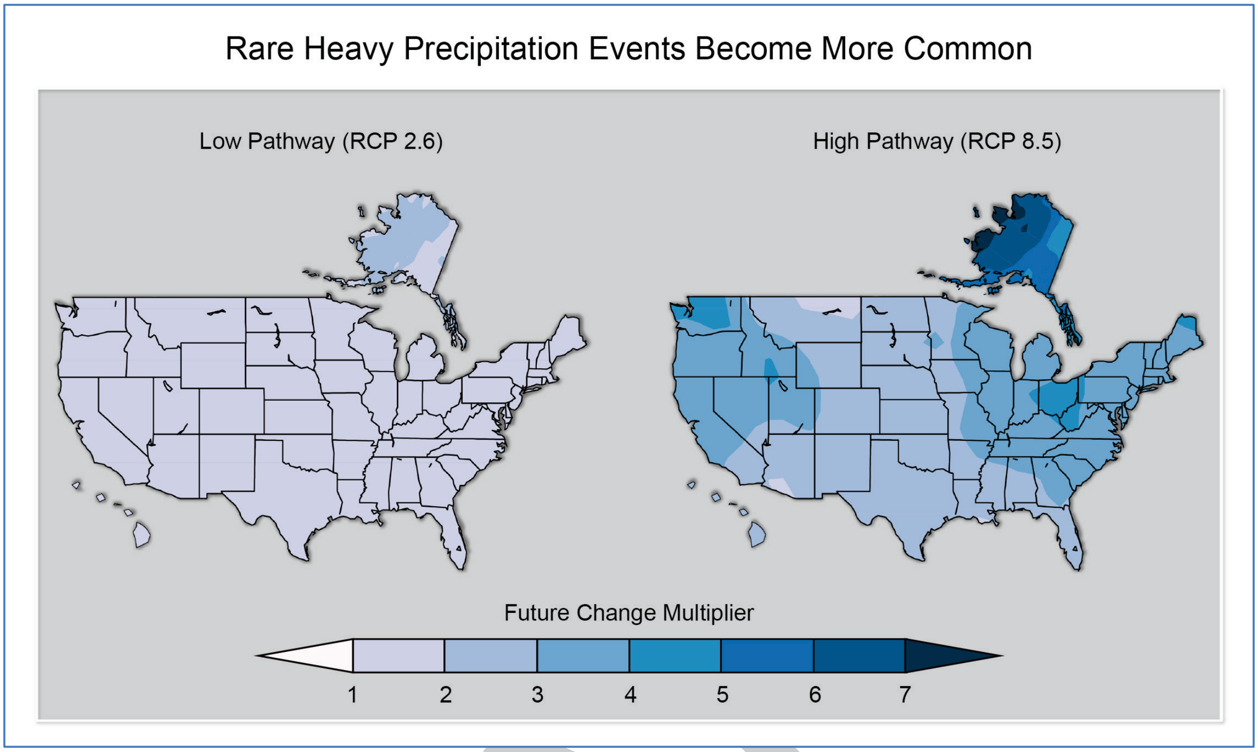

Figure 2.17: Rare Heavy Precipitation Events Become More Common

Caption: Maps show the increase in frequency of extreme daily precipitation events (now occurring about once every twenty years) by the later part of this century (2081-2100) compared to later part of last century (1981-2000). Such extreme events are projected to occur more frequently everywhere in the U.S. Under the rapid emissions reduction scenario (RCP 2.6, left), these events would occur up to about twice as often. For the scenario assuming continued increases in emissions (RCP 8.5, right), these events would occur up to five times as often. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP5; analysis by Michael Wehner, LBNL; based on methods from (Kharin et al. submitted)

Extreme Weather

Certain types of extreme weather events have become more frequent and intense, including heat waves, floods, and droughts in some regions. The increased intensity of heat waves has been most prevalent in the western parts of the country, while the intensity of flooding events has been more prevalent over the eastern parts. Droughts in the Southwest and heat waves everywhere are projected to become more intense in the future.

Heat waves are periods of abnormally and uncomfortably hot weather lasting days to weeks (Kunkel et al. 1999). 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 (Karl et al.

2009; Schwalm et al. 2012). 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 (Cook et al. 2009), contributed to the intense summer heat through depletion of soil moisture and reduction of the moderating effects of evaporation (Kunkel et al. 2008). However, recent prolonged (multi-month) extreme heat has been unprecedented. The 2011 and 2012 events set records for highest monthly average temperatures, exceeding in some cases records set in the 1930s, including the highest monthly temperature on record (July 2012, breaking the July 1936 record); for the spring and summer months, 2012 had the largest area of record-setting monthly average temperatures, including both hot daytime maximum temperatures and warm nighttime minimum temperatures (Karl et al. 2012). Corresponding with this increase in extreme heat, the number of cold waves has reached the lowest levels on record.

In the past 3 to 4 decades in the U.S. the ratio of record daily high temperatures to record daily low temperatures has steadily increased (also see Meehl et al. 2009). This ratio is now higher than in the 1930s, mostly due to the rapidly declining number of low temperature records. During this same period there has been an increasing trend in persistently high nighttime temperatures (Karl et al. 2009). In some areas, prolonged periods of record high temperatures associated with droughts contribute to dry conditions that are driving wildfires (Trenberth 2011). Numerous studies have documented that human-induced climate change has increased the frequency and severity of heat waves across the globe (Christidis et al. 2011; Stott et al. 2010).

There is emerging evidence that most of the increases of heat wave severity over the U.S. are likely due to human activity (Hansen et al. 2012; Meehl et al. 2007);, with a detectable human influence in recent heat waves in the southern Great Plains (Karl et al. 2009; Rupp et al. 2012) as well as in Europe (Stott et al. 2010; Trenberth 2011), and Russia (Christidis et al. 2011; Duffy and Tebaldi 2012; Meehl et al. 2009). Research has found that the human contribution to climate change approximately doubled the probability of the record heat in Texas in the summer of 2011 (Hoerling et al. 2012a). So while this Texas heat wave and drought could have occurred naturally, the likelihood of 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.

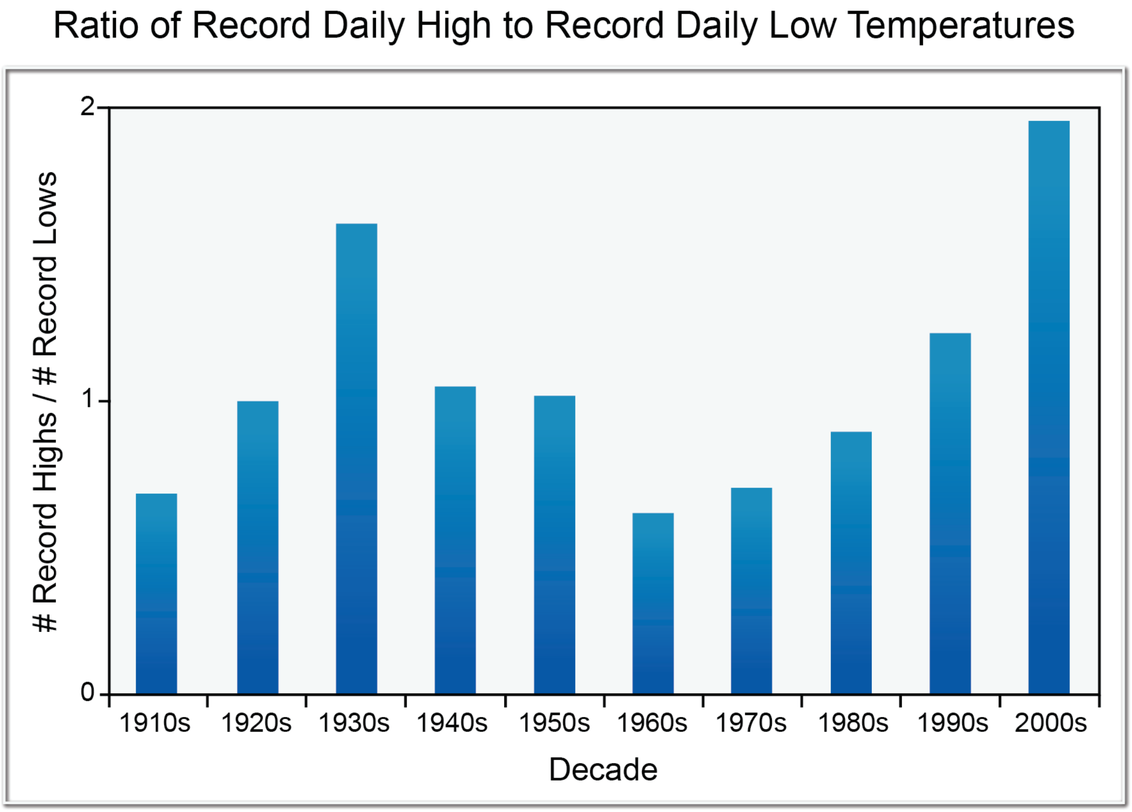

Figure 2.18: Ratio of Record Daily High to Record Daily Low Temperatures

Caption: The ratio of record daily high temperatures to record daily lows for 1911-2010 (relative to the entire history of observations) at about 1,800 weather stations in the 48 contiguous United States has increased from about 1:1 in the 1950s to about 2:1 in the most recent decade, and is higher than the ratio of 1.6:1 in the 1930s, primarily due to very small numbers of low temperature records. The ratios were even higher in 2011 and 2012, which are not shown here. (Figure source: NOAA NCDC / CICS-NC. Data from NOAA NCDC.)

Expectations for future heat wave occurrences in the U.S. are shaped by two important considerations. First, the average as well as extreme summer temperatures occurring during individual years of the past decade have approached or exceeded those of the decade of the 1930s over much of the U.S; hence summer temperatures are already moving out of their historical bounds. Second, summer drying is projected for much of the western and central U.S. As discussed below, drying exacerbates heat waves. Accordingly, the number of extremely hot days is projected to continue to increase dramatically over much of the U.S., especially by late century. 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) (Duffy and Tebaldi 2012). By the end of this century, what have previously been once-in-20-year heat waves (4-day events) are projected to occur every two or three years over most of the U.S. (Karl et al. 2008). In other words, what now seems like an extreme heat wave will become commonplace. Confidence has risen in computer model projections because recent observations are consistent with past model projections.

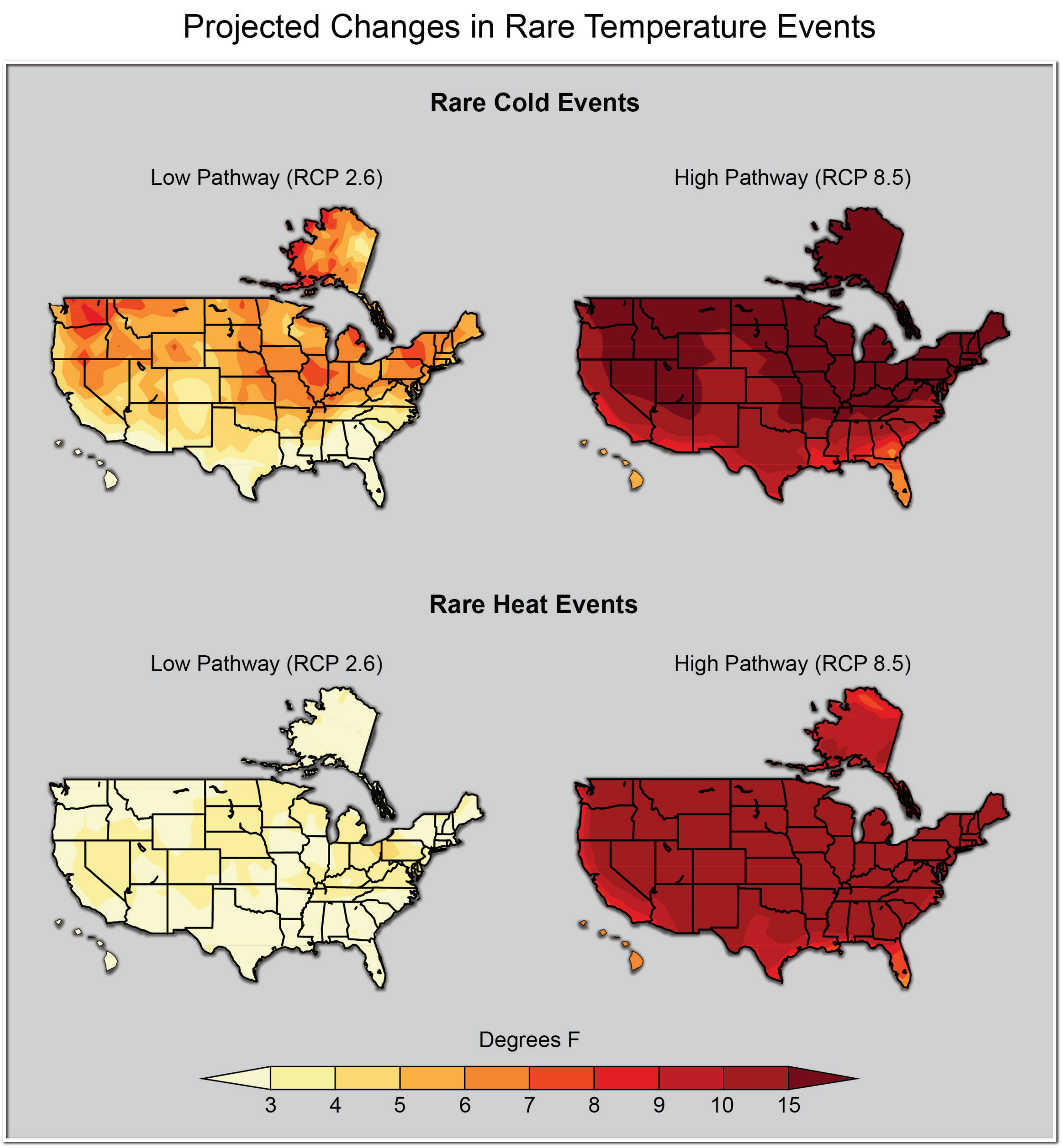

Figure 2.19: Projected Change in Rare Temperature Events

Caption: These maps show that both the hottest and coldest days are projected to be warmer. They show the projected changes in surface air temperature at the end of this century (2081-2100) relative to the end of the last century (1981-2000) on very rare cold and hot days, under a scenario that assumes rapid reductions in emissions (RCP 2.6, left) and a scenario that assumes continued increases in emissions (RCP 8.5, right). In this analysis, very rare cold and hot days are defined as those having a 5% chance of occurring during any given year. The projected temperature increases on such very cold days as well as for very hot days are larger than for the average temperature. In particular, the largest temperature increases will be on rare cold days meaning that bitter cold winter days will be much less frequent across most of the contiguous U.S. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP5; analysis by Michael Wehner, LBNL; based on method from (Kharin et al. submitted).)

In the U.S., flooding in the northern half of the eastern Great Plains and much of the Midwest has been increasing, especially over the last several decades. Flooding has decreased in the Southwest, although there have been small increases in other western states. In the areas of increased flooding, increases in both total precipitation and extreme precipitation are contributing to the flooding increases. Attribution of flood events is a relatively new area of research. There is evidence of a detectable human influence in the timing and magnitude of snowmelt and resulting streamflow in some western U.S. states (Barnett et al. 2008; Hidalgo et al. 2009; Pierce et al. 2008), in recent flooding events in England and Wales (Pall et al. 2011), and in other specific events around the globe during 2011 (Peterson et al. 2012). In general, heavier rains lead to a larger fraction of rainfall running off and, depending on the situation, more potential for flooding. While a 2-inch rain may not cause major impacts in the Southeast where such an event can occur several times a year, it can be disastrous if it occurs in the northern Great Plains.

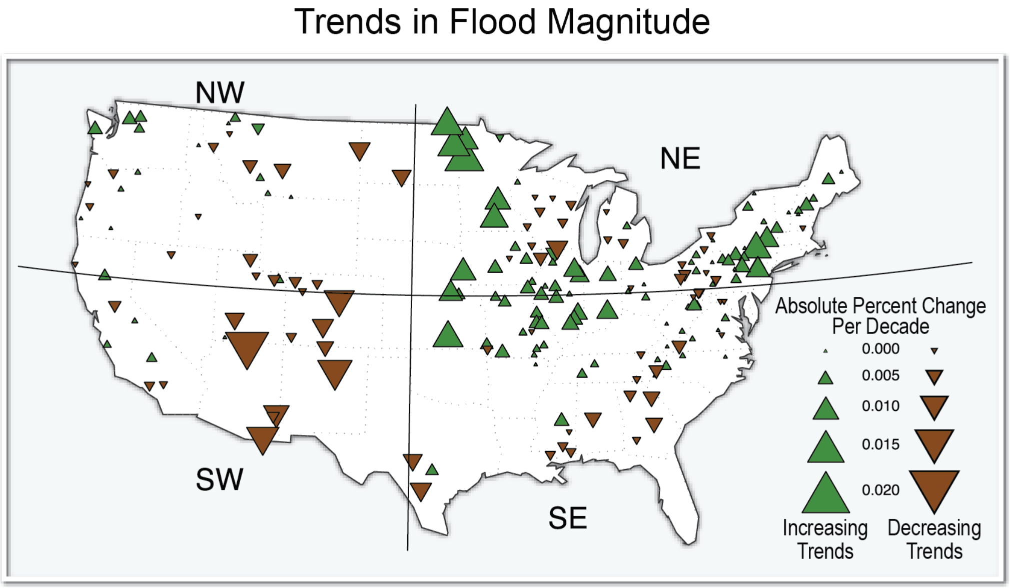

Figure 2.20: Trends in Flood Magnitude

Caption: Trend magnitude (triangle size) and direction (green = increasing trend, brown = decreasing trend) of annual flood magnitude from the 1920s through 2008. (Source: Hirsch and Ryberg 2012).

Projected higher temperatures cause increases in evaporation and loss of moisture through plant leaves, leading to drier soils. Precipitation has already declined in some areas within the Southwest and the Rocky Mountain states, and decreases in precipitation are projected to intensify in those areas and spread northward and eastward in summer (see Key Message 5). However, even in areas where precipitation does not decrease, projected higher air temperatures will cause increases in surface evaporation and loss of water from plants, leading to drier soils. 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 (Mueller and Seneviratne 2012). Under higher emissions scenarios, widespread drought is projected to become more common over most of the central and southern U.S. (Cayan et al. 2010; Dai 2012; Hoerling et al. 2012b ; Liang et al. 1996; Liang et al. 1994; Maurer et al. 2002; Nijssen et al. 1997; Schwalm et al. 2012; Wehner et al. 2011; Wood and Lettenmaier 2006; Wood et al. 2005)

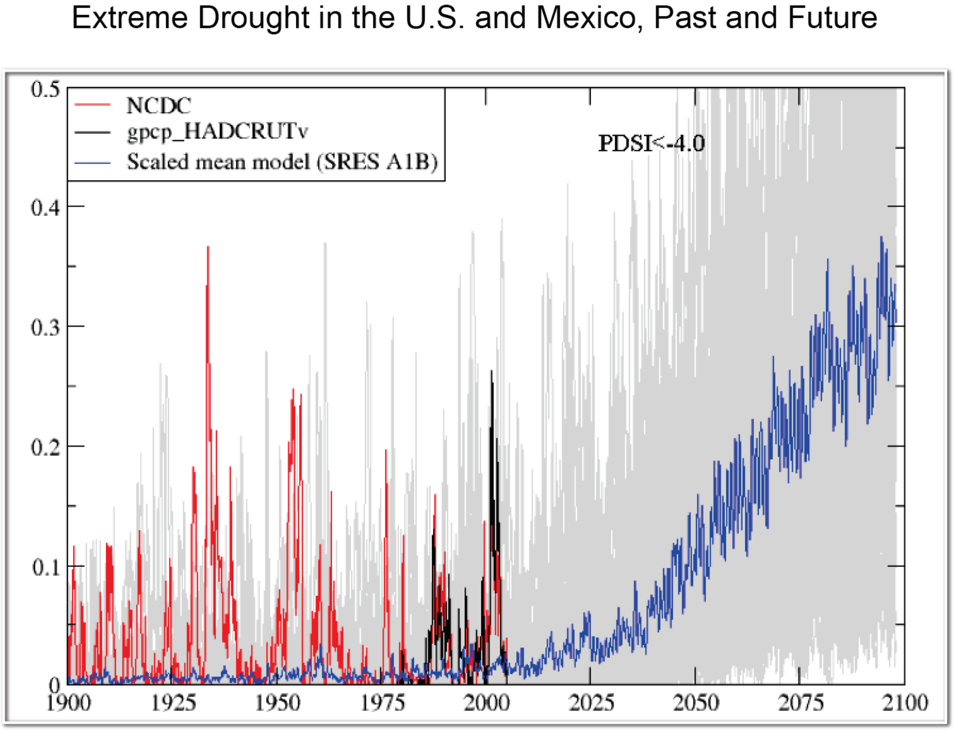

Figure 2.21: Extreme Drought in the U.S. and Mexico, Past and Future

Caption: The percentage area of the U.S. and Mexico in extreme drought according to projections of the Palmer Drought Severity Index under a mid-range emissions scenario (SRES A1B). The Palmer Drought Severity Index is the most widely used measure of drought, although it is more sensitive to temperature than other drought indices and may over-estimate the magnitude of drought increases. The red line is based on observed temperature and precipitation. The blue line is from the average of 19 different climate models. The gray lines in the background are individual results from over 70 different simulations from these models. These results suggest an increasing probability of drought over this century throughout most of the U.S. Source: (Wehner et al. 2011)

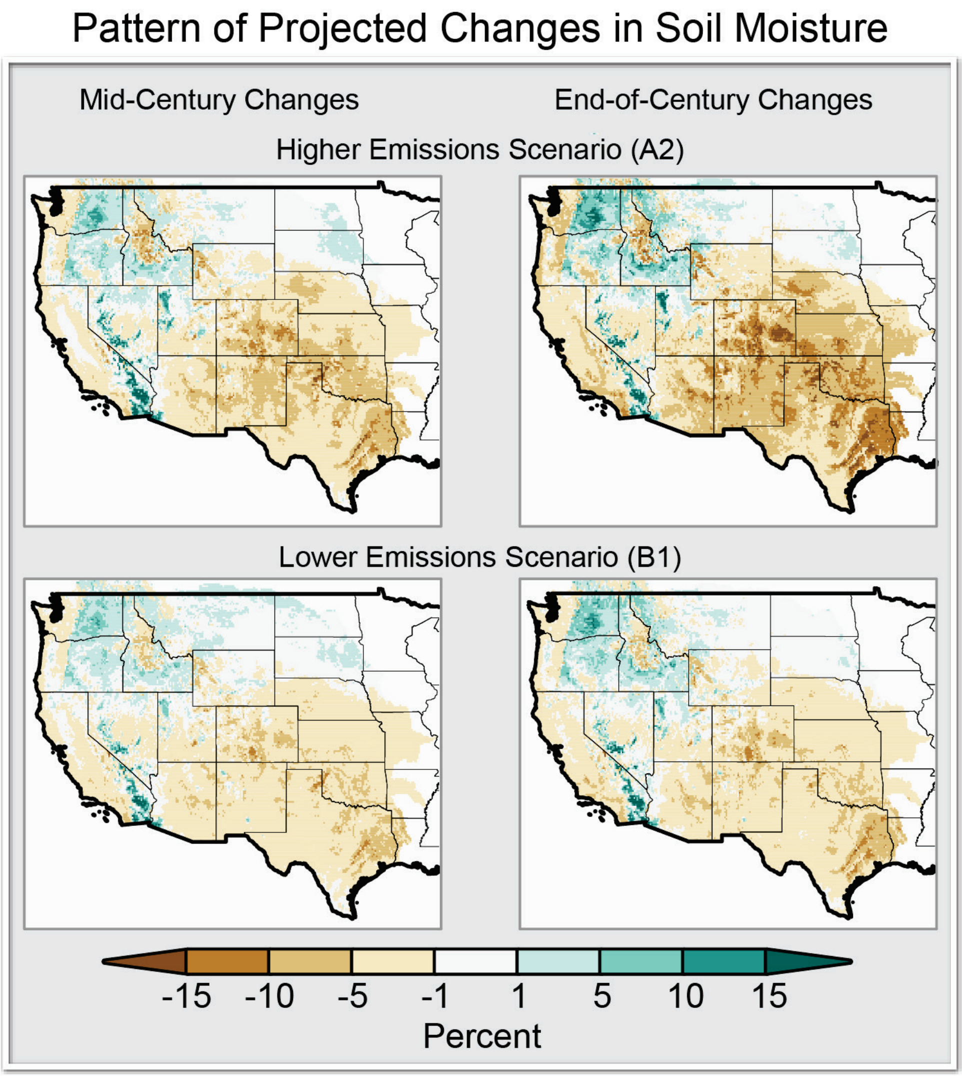

Figure 2.22: Pattern of Projected Changes in Soil Moisture

Caption: Average percent change in soil moisture compared to 1971-2000, as projected in the middle of this century (2041-2070) and late this century (2071-2100) under two emissions scenarios, a lower scenario assuming significant reductions in emissions (B1) and a higher scenario (A2) assuming that emissions continue to grow (Dai 2012; Liang et al. 1996; Liang et al. 1994; Maurer et al. 2002; Nijssen et al. 1997; Wood and Lettenmaier 2006; Wood et al. 2005). The future drying of soils in most areas simulated by this sophisticated hydrologic model (VIC model) is consistent with the future drought increases using the simpler Palmer Drought Severity Index (PDSI) metric. (Figure source: NOAA NCDC / CICS-NC. Data from VIC model.)

Changes in Storms

There has been an increase in the overall strength of hurricanes and in the number of strong (Category 4 and 5) hurricanes in the North Atlantic since the early 1980s. The intensity of the strongest hurricanes is projected to continue to increase as the oceans continue to warm. With regard to other types of storms that affect the U.S., winter storms have increased slightly in frequency and intensity, and their tracks have shifted northward over the U.S. Other trends in severe storms, including the numbers of hurricanes and 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 (snow and ice cover, ocean heat content, 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.

Hurricanes

There has been a substantial increase in virtually every measure of hurricane activity in the Atlantic since the 1970s. These increases are linked, in part, to higher sea surface temperatures in the region that Atlantic hurricanes form in and move through. Numerous factors influence these local sea surface temperatures, including human-induced emissions of heat-trapping gases and particulate pollution and natural variability (Booth et al. 2012; Camargo et al. 2012; Evan et al. 2012; Evan et al. 2011; Evan et al. 2009; Mann and Emanuel 2006; Ting et al. 2009; Zhang and Delworth 2009). However, hurricanes respond to more than just sea surface temperature. How hurricanes respond 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 (Emmanuel 2012; Zhang and Delworth 2009);. 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 heat-trapping gases. So the link between hurricanes and ocean temperatures is complex and this is an active area of research. Climate models that incorporate the best understanding of all these factors project further increases in the frequency and intensity of the strongest Atlantic hurricanes, as well as increased rainfall rates in response to continued warming of the tropical oceans by heat-trapping gases. Hurricane activity in other ocean basins has not shown such clear increases as those found in the Atlantic. Consequently, there is much greater uncertainty that hurricane activity in those basins has increased substantially in the past 40 years or so. Reducing these uncertainties is another active area of research.

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. Although recent research has yielded insights into the connections between global warming and the factors that cause tornados and severe thunderstorms (such as atmospheric instability and increases in wind speed with altitude (Del Genio et al. 2007; Trapp et al. 2007)), these relationships remain mostly unexplored, largely because of the challenges in observing thunderstorms and tornadoes and simulating them with computer models.

Winter Storms

Over the U.S., changes in winter storm frequency and intensity are small and not significant, with the exception that there is limited evidence of an overall increase in storm activity near the northeast and northwest U.S. coastlines during the second half of the 1950-2010 period (Vose, 2012). However, for the Northern Hemisphere as a whole, there is evidence of an increase in both storm frequency and intensity during the cold season since 1950 (Vose, 2012), with storm tracks having shifted slightly towards the poles (Wang et al. 2006; Wang et al. 2012). Extremely heavy snowstorms increased in number during the last century in northern and eastern parts of the U.S., but have been less frequent since 2000 (Kunkel et al. 2012h; Squires et al. 2009). Total seasonal snowfall has generally decreased in southern and some western areas (Kunkel et al. 2009b), increased in the northern Plains and Great Lakes (Kunkel et al. 2009a, 2009b), and not changed in other areas, such as the Sierra Nevada (Christy 2012). 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 (Kunkel et al. 2009). 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 of the wintertime circulation of the Northern Hemisphere (Francis and Vavrus 2012). Overall snow cover has decreased in the Northern Hemisphere, due in part to higher temperatures that shorten the time snow spends on the ground (BAMS 2012).

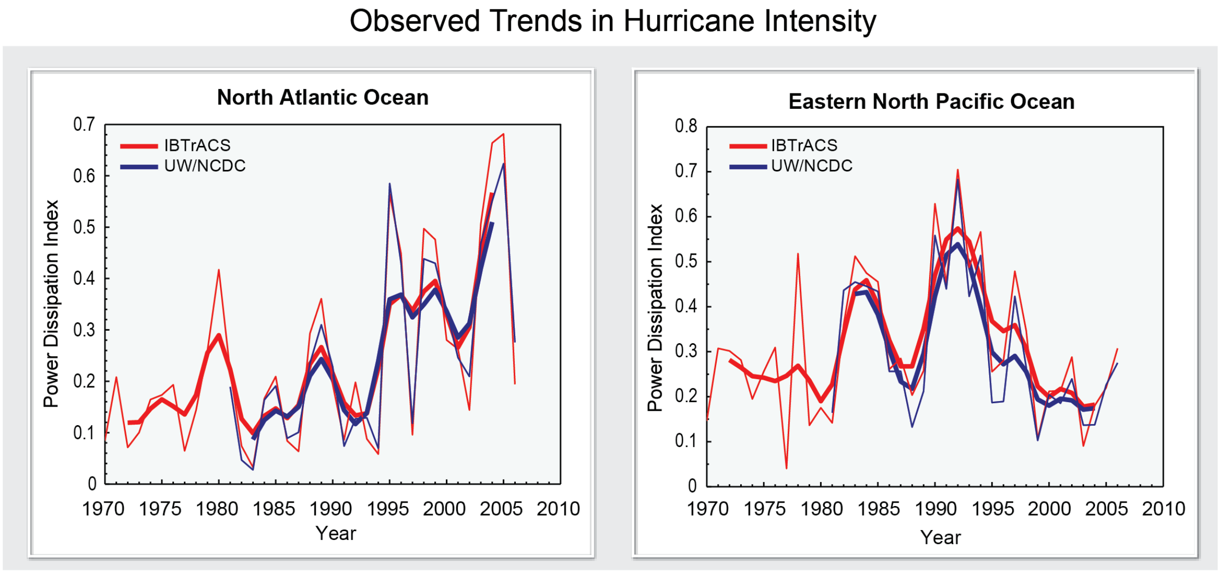

Figure 2.23: Observed Trends in Hurricane Intensity

Caption: Recent variations of the Power Dissipation Index (PDI), a measure of overall hurricane intensity in a hurricane season. Historical and satellite observations show a significant upward trend in the strength of hurricanes and in the number of strong hurricanes (Category 4 and 5) in the North Atlantic from 1983 to 2009. A significant decreasing trend in hurricane intensity is detected for the eastern North Pacific from 1984 to 2009, but no trend in the number of storms is apparent. Updated from (Kossin et al. 2007)

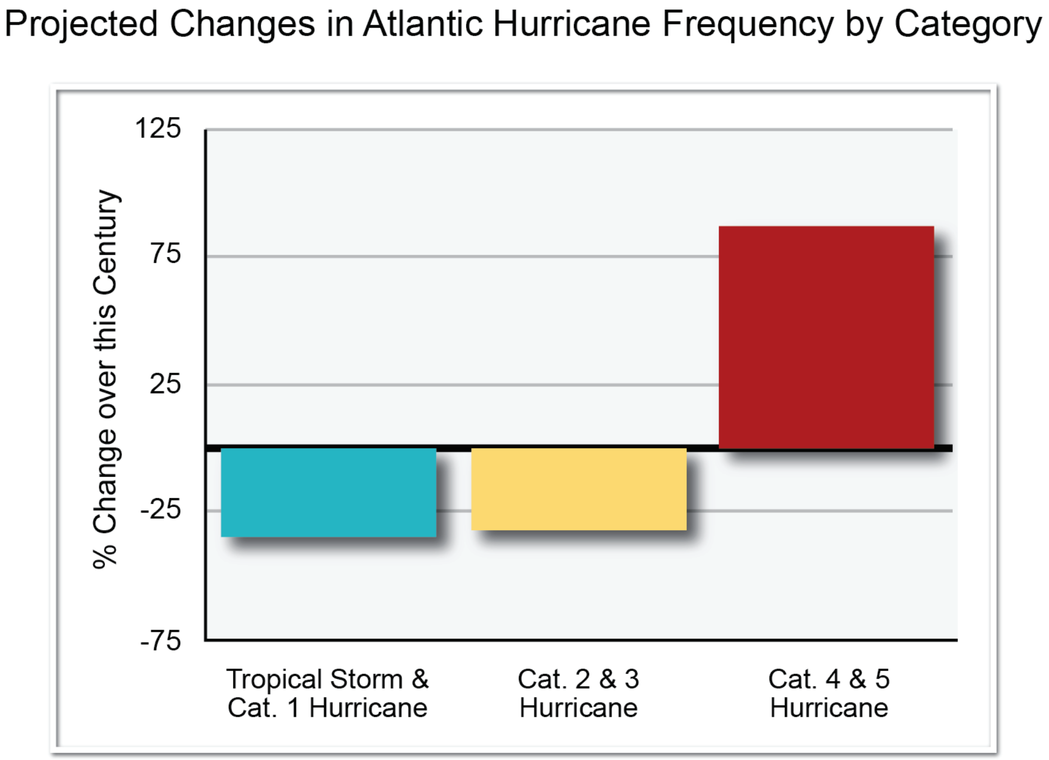

Figure 2.24: Projected Changes in Atlantic Hurricane Frequency by Category

Caption: Model projections of percentage changes in Atlantic hurricane and tropical storm frequencies for different storm categories, by the late this century. Projected changes are for the period 2081-2100 compared with the period 2001-2020. (Figure source: NOAA GFDL)

Sea Level Rise

Global sea level has risen by about 8 inches since 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 (Church et al. 2011). 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 (Arctic Monitoring and Assessment Programme 2011).

Since the late 1800s, tide gauges throughout the world have shown that global sea level has risen by about 8 inches. Proxy data have shown that this rate of sea level rise is faster than at any time in at least the past 2000 years (Kemp et al. 2012). 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 that the current rate is faster still (Church and White 2011a).

Projecting future rates of sea level rise is challenging. Even the most sophisticated climate models, which explicitly represent Earth's physical processes, cannot simulate recent rapid changes in ice sheet dynamics, and thus tend to underestimate sea level rise. In recent years, "semi-empirical" models, based on statistical relationships between historical rates of global warming and sea level rise, have been developed. Early efforts at semi-empirical models suggested much higher rates of sea level rise (as much as 6 feet by 2100) (Jevrejeva et al. 2010; Vermeer and Rahmstorf 2009). More recent semi-empirical models have suggested upper ends closer to 3 or 4 feet by 2100 (Jevrejeva et al. 2012; Rahmstorf et al. 2012). It is not clear, however, whether these statistical relationships will hold in the future.

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 (Yin 2012) and the melting of small mountain glaciers (Marzeion et al. 2012) 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. (Gladstone et al. 2012; Jevrejeva et al. 2012; Joughin et al. 2010; Katsman et al. 2011; Rahmstorf et al. 2012). 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 (Burkett and Davidson 2012; Parris et al. 2012). In particular, the high end of these scenarios may be useful for decision makers with a low tolerance for risk (Burkett and Davidson 2012; Parris et al. 2012) (see figure on global sea level rise). 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. 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 (Strauss et al.

2012). Sea level rise is not expected to stop in 2100. 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.

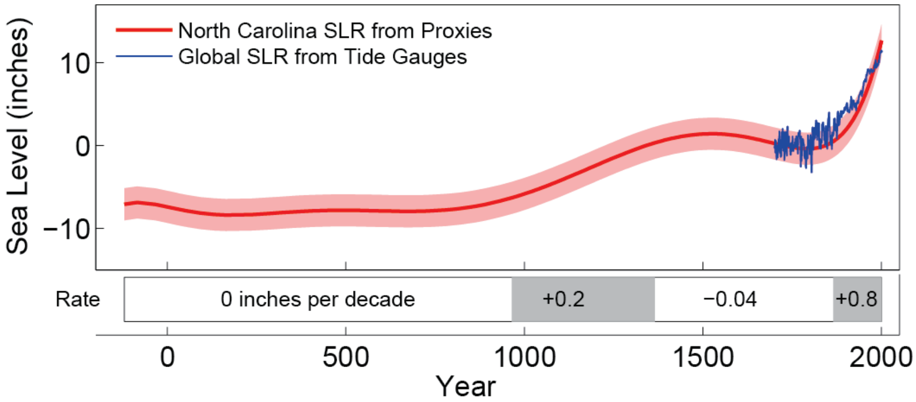

Figure 2.25

Caption: Rates of sea level change in the North Atlantic Ocean based on data collected from the U.S. East Coast (Kemp et al. 2012) (red line, pink band shows the uncertainty range) compared with a reconstruction of global sea level rise based on tide gauge data (Jevrejeva et al. 2008) (blue line). (Figure source: Josh Willis, NASA Jet Propulsion Laboratory)

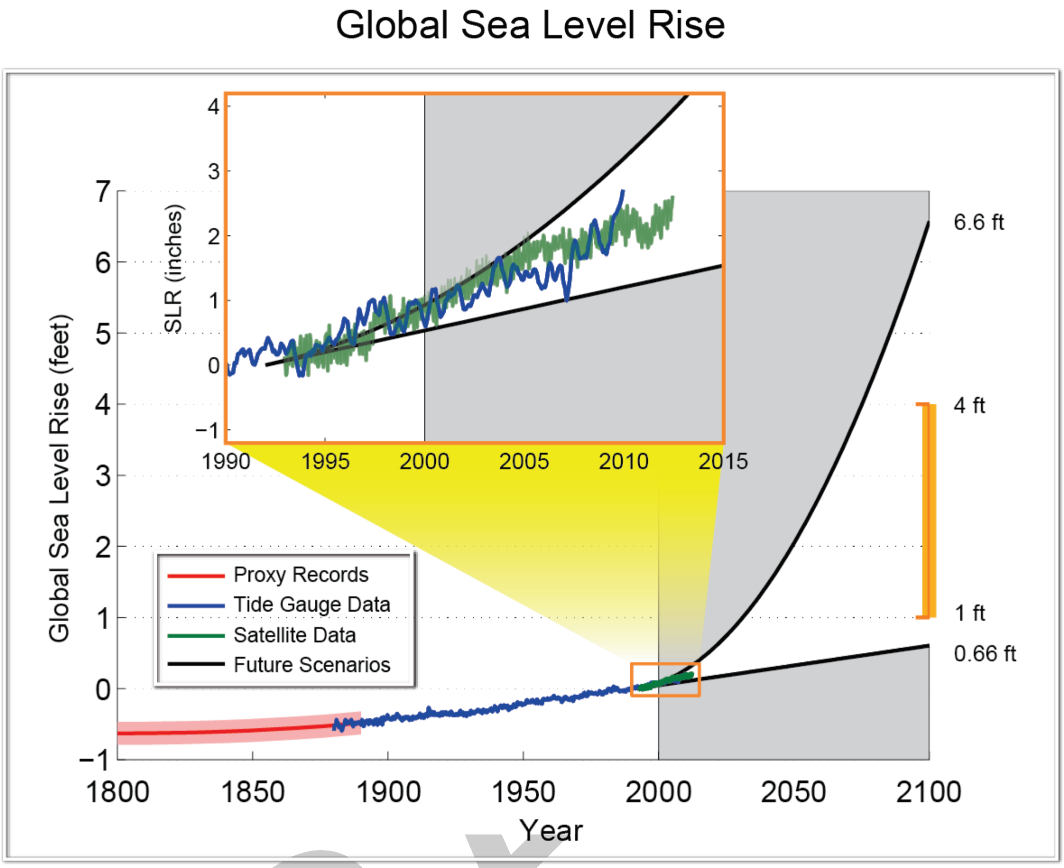

Figure 2.26: Global Sea Level Rise

Caption: Estimated, observed and possible amounts of global sea level rise from 1800 to 2100. Proxy estimates (Kemp et al. 2012) (for example, based on sediment records) are shown in red (pink band shows uncertainty), tide gauge data in blue (Church and White 2011a), and satellite observations are shown in green (Nerem et al. 2010). The future scenarios range from 0.66 feet to 6.6 feet in 2100 (Parris et al. 2012). Higher or lower amounts of sea level rise are considered implausible, as represented by the gray shading. 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: Josh Willis, NASA Jet Propulsion Laboratory)

Melting Ice

Rising temperatures are reducing ice on land, lakes, and sea. This loss of ice is expected to continue.

Rising temperatures across the U.S. have reduced lake ice, sea ice, glaciers, and seasonal snow cover over the last few decades (Arctic Monitoring and Assessment Programme 2011). In the Great Lakes, for example, total winter ice coverage has decreased by 63% since the early 1970s (Wang et al. 2011).

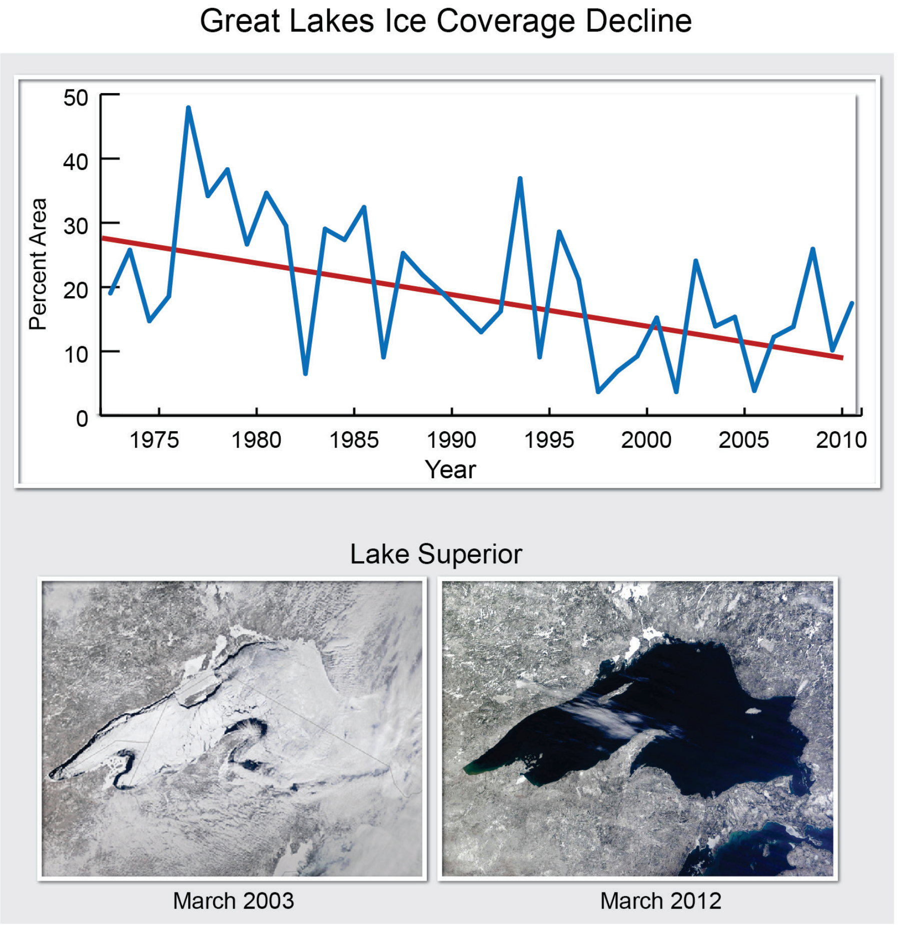

Figure 2.27: Great Lakes Ice Coverage Decline

Caption: Blue line shows annual average Great Lakes ice coverage from 1973 to 2011 and red line shows the trend. (Figure source updated from Wang et al. 2011) Satellite images show Lake Superior in a high ice year and a more recent low ice year. (Satellite images courtesy of NASA)

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% (NSIDC 2012). This decline is unprecedented in the historical record and is consistent with human-induced climate change. 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 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 (Francis and Vavrus 2012; Liu et al. 2012).

Arctic Sea Ice Decline

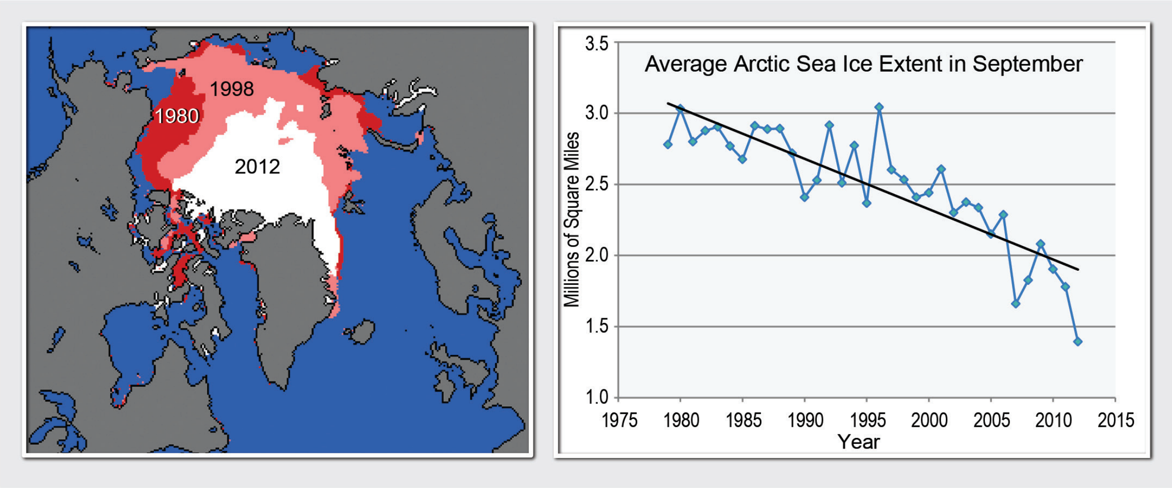

Figure 2.28: Arctic Sea Ice Decline

Caption: 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 figure on the left, was more than 40% below the median for 1979-2000. It is also notable that the ice has become much thinner in recent years, so its total volume has declined even more rapidly than the extent shown here (Arctic Monitoring and Assessment Programme 2011). The graph on the right shows annual variations in September Arctic sea ice extent for 1979-2012. (Figure and data from National Snow and Ice Data Center)

The loss of sea ice has been greater in summer than in winter. The Bering Sea, for example, experiences sea ice only in the winter-spring portion of the year, and shows no trend in ice coverage 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. Sea ice in the Antarctic is largely seasonal and has shown a slight increase in extent since 1979.

This seasonal pattern of observed ice loss 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 summer sea ice in the Arctic Ocean could disappear before mid-century under scenarios that assume continued growth in global emissions, although sea ice would still form in winter (Stroeve et al. 2012; Wang and Overland 2009). Even during a long-term decrease, occasional temporary increases in Arctic summer ice can be expected over timescales of a decade or so because of internal variability (Kay et al. 2011).

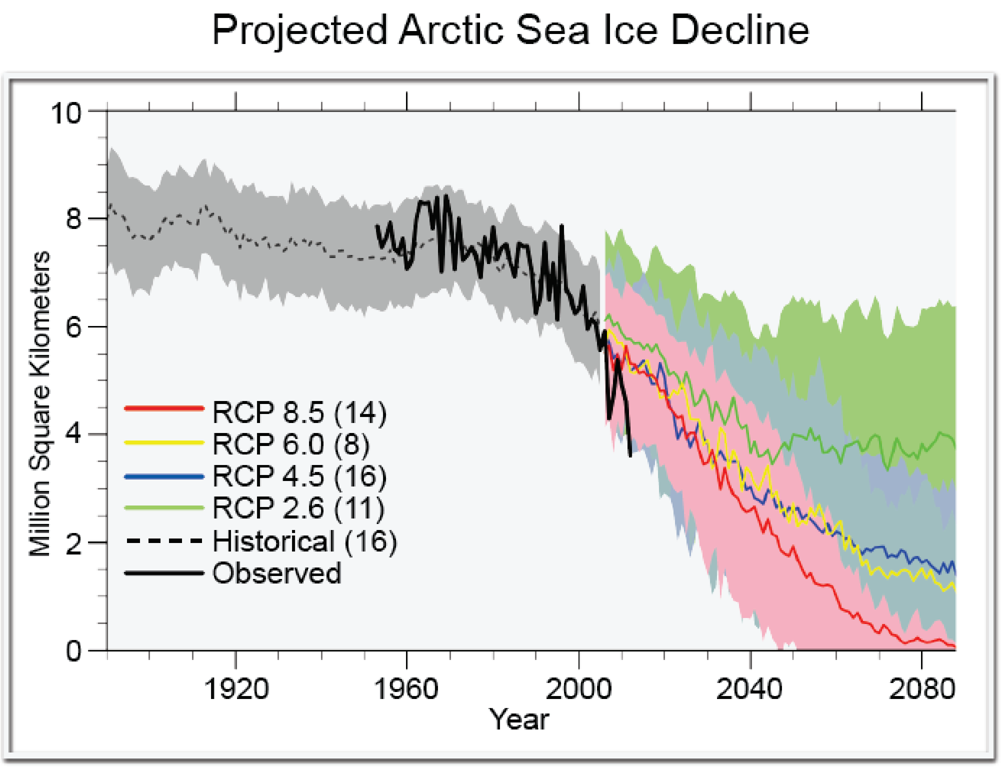

Figure 2.29: Projected Arctic Sea Ice Decline

Caption: 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 emissions scenarios: RCP 2.6 (green line), RCP 4.5 (blue line), RCP 6.0 (yellow line), and RCP 8.5 (red line); numbers in parentheses denote number of models represented. Colored lines for RCP scenarios are model averages (CMIP5). Shading shows ranges among models (pink for RCP 8.5 simulations, blue for RCP 4.5 simulations). The thick black line shows observed data for 1953-2012. These newer model simulations project acceleration in sea ice loss relative to older simulations. (Figure source: adapted from Stroeve et al. 2012).

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 (Fettweis et al. 2011), culminating in summer 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 has accelerated in recent decades, increasing Greenland's contribution to sea level rise (Dahl-Jensen et al. 2011). The proportion of global sea level rise coming from Greenland is expected to continue to increase (Dahl-Jensen et al. 2011). However, the dynamics of the Greenland Ice Sheet are generally not included in present global climate models.

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. Methane emissions have been detected from Alaskan lakes underlain by permafrost (Walter et al. 2007), and measurements suggest potentially even greater releases from the Arctic continental shelf in the East Siberian Sea (Shakhova et al. 2010).

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 potential 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 (Doney et al. 2009). Currently, the oceans absorbs about a quarter of the CO_2 humans produce every year (Le Quere et al. 2009). Over the last 250 years, the oceans have absorbed 530 billion tons of CO_2, increasing the acidity of surface waters by 30% (Caldeira and Wickett 2003; Hall-Spencer et al. 2008; Hönisch et al. 2012). Although the average oceanic pH can vary on interglacial timescales (Caldeira and Wickett 2003), the current observed rate of change is roughly 50 times faster than known historical change (Byrne et al. 2010). Regional factors such as coastal upwelling (Feely et al. 2008), changes in riverine and glacial discharge rates (Mathis et al. 2011), sea ice loss (Yamamoto-Kawai et al. 2009), and urbanization (Feely et al. 2010) 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 mineral 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 concentrations. Recent analyses show that large areas of the oceans along the U.S. west coast (Gruber et al. 2012), the Bering Sea, and the western Arctic Ocean (Orr et al. 2005) 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 (Doney et al. 2012; Fabry et al. 2009).

Projections indicate that in a high emissions scenario such as SRES A2 or RCP 8.5, current pH could be reduced from the current level of 8.07 to as low as 7.67 by the end of the century, roughly five times the amount of acidification that has already occurred (NOAA 2012). Such large changes in ocean pH have probably not been experienced on the planet for the past 21 million years, and scientists are unsure whether and how quickly ocean life could adapt to such rapid acidification.

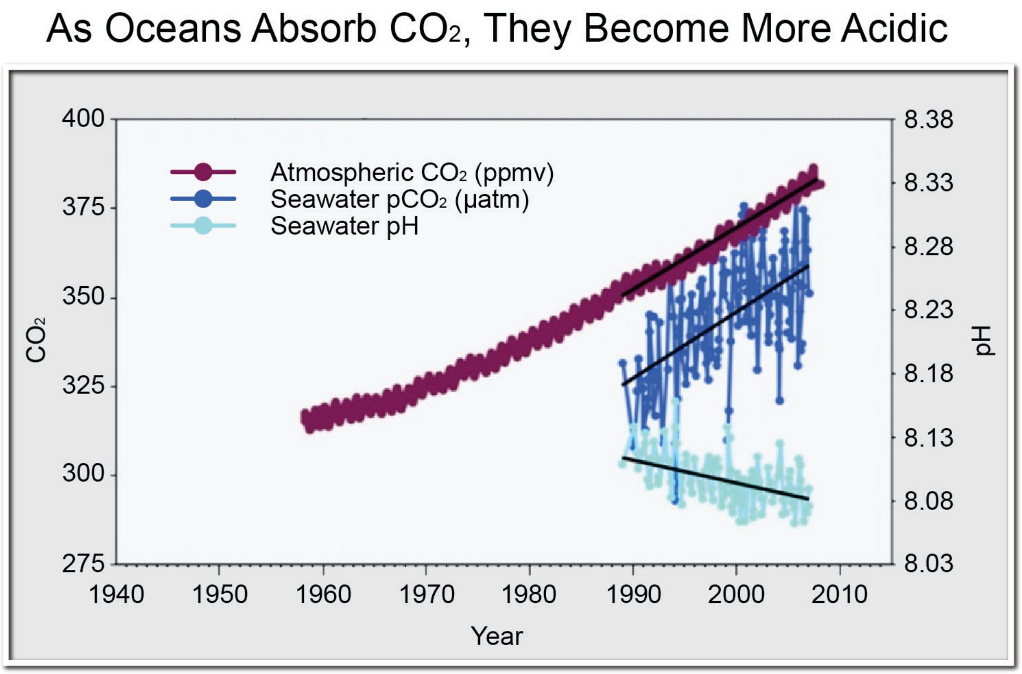

Figure 2.30: As Oceans Absorb CO_2, They Become More Acidic

Caption: The correlation between rising levels of carbon dioxide in the atmosphere at Mauna Loa with rising carbon dioxide levels and falling pH in the nearby ocean at Station Aloha. As carbon dioxide accumulates in the ocean, the water becomes more acidic. Figure source: modified from (Feel.y et al. 2008).

Figure 2.31: Shells Dissolve in Acidified Ocean Water

Caption: The Pteropod, or "sea butterfly", is a tiny sea creature about the size of a small pea. Pteropods are eaten by marine species ranging in size from krill to whales and are a major source of food for North Pacific young salmon. The photos above show what happens to a pteropod's shell when placed in seawater with pH and carbonate levels projected for the year 2100. The shell slowly dissolves after 45 days. (Photo credit: National Geographic Images)

Traceable Accounts

Chapter 2: Our Changing Climate

Key Message Process: Development of the key messages involved: 1) discussions of the lead authors and accompanying analyses conducted via one in-person meeting plus a number of teleconferences over the last 8 months (from February thru September 2012) including reviews of the scientific literature; and 2) the findings from four special workshops that related to the latest science 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 resulted in a paper submitted to BAMS (2012). The first was held in July 2011, titled Monitoring Changes in Extreme Storm Statistics: State of Knowledge (https://sites.google.com/a/noaa.gov/severe-storms-workshop/). The second was held in November 2011, titled November 2011 – Forum on Trends and Causes of Observed Changes in Heatwaves, Coldwaves, Floods, and Drought (https://sites.google.com/a/noaa.gov/heatwaves-coldwaves-floods-droughts/). The third was held in January 2012, titled Forum on Trends in Extreme Winds, Waves, and Extratropical Storms along the Coasts (https://sites.google.com/a/noaa.gov/extreme-winds-waves-extratropical-storms/). The fourth, the CMIP5 results workshop, was held in March 2012 in Hawaii.

In developing key messages, the Chapter Author Team engaged in multiple technical discussions over the last 8 months via teleconferences and emails as they reviewed over 80 technical inputs provided by the public, as well as other published literature, and professional judgment. These discussions were supported by targeted consultation with additional experts, and they were based on criteria that help define "key vulnerabilities." A consensus-based approach was used for final key message selection.

Key message #1/11	**Global climate is changing now and this change is apparent across a wide range of observations. The climate change 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. Generally, those reports did not add much to the author team's process in the way of observation and model data analyses and their use of the peer-reviewed literature. 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 (Kennedy et al. 2010). Changes in the mean state have been accompanied by changes in the frequency and nature of extreme events (Alexander et al. 2006) . 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(Gillett et al. 2012; Stott et al. 2010). The influence of human impacts on the climate system was also observed in a number of individual climate variables (AchutaRao et al. 2006; Gillett and Stott 2009; Min et al. 2011; Pall et al. 2011; Santer et al. 2007; Santer 2012; Willett et al. 2007) .
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 US Climate Reference Network can all reduce uncertainties.
Assessment of confidence based	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

on evidence	uncertainties. All observational evidence is consistent with a warming climate since the late 1800's. There is **very high** confidence that the 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.

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

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #2/11	**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 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 (IPCC 2007; Schnellnhuber et al. 2006; Taylor et al. 2012). Evidence that the planet has warmed is "unequivocal" (IPCC 2007) , and is corroborated though multiple lines of evidence, as is the conclusion that the causes are very likely human in origin. 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	There are several major sources of uncertainty in making projections of climate change. The relative importance of these changes over time. In 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. Uncertainty in natural climate drivers, e.g. how much will the solar output 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 global climate is projected to continue to change over this century and beyond**.**

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

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #3/11	**U.S. average temperature has increased by about 1.5 degrees F since record keeping began in 1895; more than 80% of this increase has occurred since 1980. The most recent decade was the nation's warmest on record. U.S. temperatures 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, 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. With the increasing understanding of U.S. temperature measurements, (Fall et al. 2010; Fall et al. 2011; Karl et al. 1986; Menne and Williams Jr 2009; Menne et al. 2009; Menne et al. 2010; Vose et al. 2012; Williams et al. 2012) a temperature increase has been observed and is projected to continue rising (Menne et al. 2009). 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 U.S. 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	There have been substantial advances in our understanding of the U.S. temperature record since the previous National Climate Assessment (Fall et al. 2010; Fall et al. 2011; Karl et al. 2009; Menne and Williams Jr 2009; Menne et al. 2009; Menne et al. 2010; Vose et al. 2012; Williams et al. 2012). A potential uncertainty is the sensitivity of temperature trends to bias 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 While numerous studies verify the efficacy of the bias 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 in a warming climate.
Assessment of confidence based on evidence	Given the evidence base and remaining uncertainties, confidence is **very high** that because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, smooth across the country or over time.

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

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #4/11	**The length of the frost-free season (and the corresponding growing season) is increasing nationally, with the largest increases occurring in the western U.S., affecting ecosystems and agriculture. Continued lengthening of the growing seasons across the U.S. is projected.**
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 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 of increasing number of frost-free days are similar to changes in mean temperature. Separate analysis of surface data also indicates a trend towards an earlier onset of spring. Key references: U.S. Environmental Protection Agency (2010), Dragoni et al. (2011), Jeong et al.(2011), Ziska et al.(2011). Nearly all studies to date published in the peer-reviewed literature (e.g., Dragoni et al. (2011), U.S. Environmental Protection Agency (2010), Jeong et al.(2011)) agree that the freeze-free and growing seasons have lengthened. This is most apparent in the western U.S. 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.
New information and remaining uncertainties	A key issue (uncertainty) is the potential effect of station inhomogeneities on observed trends, 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) is increasing nationally, with the largest increases occurring in the western U.S, affecting ecosystems, gardening, and agriculture. Confidence is **very high** that there will be continued lengthening of these seasons across the U.S. given the evidence base.

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

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #5/11	**Precipitation over the U.S. has increased on average during the period since 1900, with the largest increases the Midwest, southern Great Plains, and Northeast. Portions of the Southeast, the Southwest, and the Rocky Mountain states have experienced decreases. More winter and spring precipitation is projected for the northern U.S., 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 of daily observations from the U.S. Cooperative Observer Network. Published work shows the regional differences in precipitation (McRoberts and Nielsen-Gammon 2011; Peterson et al. 2012) . 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 (e.g., IPCC 2007).
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 extent to which observed regional variations will persist into the future. An uncertainty in projected precipitation concerns the extent of the drying of the Southwest. Shifts in precipitation patterns due to changes in pollution are uncertain and is 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 (e.g., (McRoberts and Nielsen-Gammon 2011; Peterson et al. 2012)) 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 precipitation over the U.S. has increased on average during the period since 1900, with the largest increases the Midwest, southern Great Plains, and Northeast. Confidence is **high** given the evidence base and uncertainties that portions of the Southeast, the Southwest, and the Rocky Mountain states have experienced precipitation decreases. There **is less certainty** for Southwest mountain states because they sit in the transition region. 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.

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

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #6/11	**Heavy downpours are increasing nationally, especially over the last three to five decades. Largest increases are in the Midwest and Northeast. Further increases in the frequency and intensity of extreme precipitation events are projected for most U.S. areas.**
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 of hourly and daily precipitation observations from the U.S. Cooperative Observer Network and is supported by observed increases in atmospheric water vapor (Dai 2012). Recent publications have projected an increase in extreme precipitation events (Kunkel et al. 2012h; Wang and Overland 2009), with some areas getting larger increases (Karl et al. 2009) and some getting decreases (Wehner 2012; Wuebbles et al. 2012). 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 likely 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 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 nationally, 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.

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

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #7/11	**Certain types of extreme weather events have become more frequent and intense, including heat waves, floods, and droughts in some regions. The increased intensity of heat waves has been most prevalent in the western parts of the country, while the intensity of flooding events has been more prevalent over the eastern parts. Droughts in the Southwest and heat waves everywhere are projected to become more intense in the future.**
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. Evidence for these trends in the United States is provided by Meehl et al.(2009). Cited papers by Stott et al. (2010) and Christidis et al.(2011) contain evidence for the corresponding trends in a global framework. A number of publications have explored the increasing trend of heat waves (Karl et al. 2008; Stott et al. 2010; Trenberth 2011). Additionally, heat waves observed in the southern Great Plains (Karl et al. 2009), Europe (Stott et al. 2010; Trenberth 2011) and Russia (Christidis et al. 2011; Duffy and Tebaldi 2012; Meehl et al. 2009) 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 (Barnett et al. 2008; Hidalgo et al. 2009; Pall et al. 2011; Peterson et al. 2012; Pierce et al. 2008). Further evidence for these trends is provided by Trenberth (2011). Projections of increased drought are supported by the results of Wehner et al.(2011), with a number of publications projecting drought as becoming a more normal condition over much of the southern and central U.S. (most recent references: Dai 2012; Hoerling et al. 2012b). 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. 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 extreme event occurrences in shorter timescales (several years to decades), but the changes become larger relative to natural variability as the timescale lengthens. Stakeholders should view the occurrence of extreme events in the context of increasing probabilities. Continuation of long term temperature and precipitation observations is critical to monitoring trends in extreme weather events.
Assessment of confidence based on evidence	Give the evidence base and uncertainties: Heat waves have become more frequent and intense, and confidence is **high** that these trends are projected to continue. Droughts have become more frequent and intense in some regions, and confidence is **high** that these trends are projected to continue.

	Floods have become more frequent and intense in some regions, and confidence is **medium** to **high** that these trends are projected to continue.

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

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Key Message Process: See KM#1.

Key message #8/11	**There has been an increase in the overall strength of hurricanes and in the number of strong (Category 4 and 5) hurricanes in the North Atlantic since the early 1980s. The intensity of the strongest hurricanes is projected to continue to increase as the oceans continue to warm. With regard to other types of storms that affect the U.S., winter storms have increased slightly in frequency and intensity, and their tracks have shifted northward over the U.S. Other trends in severe storms, including the numbers of hurricanes and 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 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. Recent studies suggest that the most intense Atlantic hurricanes have become stronger since the early 1980s, as documented by (Kossin et al. 2007) . While this is still the subject of active research, this trend is projected to continue (Bender et al. 2010). Current work by Vose et al. (2012) has provided evidence in the increase in frequency and intensity of winter storms, with the storm tracks shifting poleward (Wang et al. 2006; Wang et al. 2012), but some areas have experienced a decrease in winter storm frequency (Karl et al. 2009). Some recent research has provided insight into the connection of global warming to tornados and severe thunderstorms (Del Genio et al. 2007; Trapp et al. 2007).
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. Significant uncertainties remain in making projections of hurricane number and intensity. While the best analyses to date suggest an increase in intensity and in the number of most intense storms over the century, there remain significant uncertainties. The figure in the chapter for KM#8 that shows projected changes in occurrences of hurricanes of different intensities includes data points from different models, illustrating the spread. Other types of storms have even greater uncertainties in their recent trends and projections. The text for this key message explicitly acknowledges the state of knowledge, pointing out “what we don’t know”.
Assessment of confidence based on evidence	Given the evidence and uncertainties, confidence is **medium** that the strongest hurricanes are projected to increase in intensity as the oceans warm due to more available energy. Confidence is **low** regarding other trends in severe storms due to the many uncertainties that remain about frequency and intensity of other types of storms.

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

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Key Message Process: See KM#1.

Key message #9/11	**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 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 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 (Kemp et al. 2012; Parris et al. 2012) and project that future sea level rise over the rest of this century will be faster than those of the last 100 years (Parris et al. 2012; Willis et al. 2010).
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) (Jevrejeva et al. 2010; Vermeer and Rahmstorf 2009). More recent semi-empirical models have suggested upper bounds closer to 3 or 4 feet (Jevrejeva et al. 2012; Rahmstorf et al. 2012). It is not clear, however, whether these statistical relationships will hold in the future. More recent work suggests that a high-end of 3 to 4 feet is more plausible. (Gladstone et al. 2012; Jevrejeva et al. 2012; Joughin et al. 2010; Katsman et al. 2011; Rahmstorf et al. 2012). 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 (Burkett and Davidson 2012; Parris et al. 2012) .
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. Given the evidence and uncertainties about ice sheet dynamics, confidence is **high** that the rate of global sea level rise has been faster since the early 1990s, but there is **medium** confidence in global sea level rise will be in the range of 1 to 4 feet by 2100.

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

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Key Message Process: See KM#1.

Key message #10/11	**Rising temperatures are reducing ice on land, lakes, and sea. This loss of ice is expected to continue.**
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. There have been a number of publications reporting decreases in ice on land (Fettweis et al. 2011) and glacier recession . Evidence that winter lake ice and summer sea ice are rapidly declining is based on satellite data and is incontrovertible (for lake ice Arctic Monitoring and Assessment Programme 2011; Wang et al. 2012). Nearly all studies to date published in the peer-reviewed literature agree that summer Arctic sea ice extent is rapidly declining and that if heat-trapping gas concentrations continue to rise, an essentially ice-free Arctic ocean will be realized sometime during this century (e.g., Stroeve et al. 2012; KM 10). September 2012 has 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 (Arctic Monitoring and Assessment Programme 2011). The rate of permafrost degradation is complicated by changes in snow cover and vegetation.
New information and remaining uncertainties	A key issue (uncertainty) is the rate of sea-ice loss through this century, which stems from a combination of large differences in projections between different climate models, natural climate variability and future rates of fossil fuel emissions. This uncertainty is illustrated in the figure showing the CMIP5-based projections (from Stroeve et al. 2012). 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 melting sea ice, lake ice, and glaciers and that this melting is expected to continue. Given the evidence base and uncertainties, confidence is **high** that rising temperatures are thawing permafrost and that this thawing is expected to continue.

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

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Key Message Process: See KM#1.

Key message #11/11	**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 potential impacts on marine ecosystems.**
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. Work done by LeQuere et al. 2009 reported that the oceans currently absorb a quarter of anthropogenic CO_2. Publications have shown that this absorption causes the ocean to become more acidic (Doney et al. 2009). Recent publications demonstrate the adverse effects further acidification will have on marine life (Doney et al. 2012; Fabry et al. 2009; Gruber et al. 2012; Orr et al. 2005).
New information and remaining uncertainties	The key issue is to understand how future levels of ocean acidity will affect marine ecosystems. Absorption of anthropogenic CO_2, reduced pH, and lower calcium carbonate (CaCO3) saturation in surface waters, where the bulk of oceanic production occurs, are well verified from models, hydrographic surveys, and time series data(Orr et al. 2005).
Assessment of confidence based on evidence	**Very high** for trend of ocean acidification; **low-to-medium** for ecological consequences. Our present understanding of potential ocean acidification impacts on marine organisms stems largely from short-term laboratory and mesocosm experiments; consequently, the response of individual organisms, populations, and communities to more realistic gradual changes is largely unknown. Given the evidence base and uncertainties, confidence is **very high** that oceans are absorbing a quarter of emitted CO2.

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

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