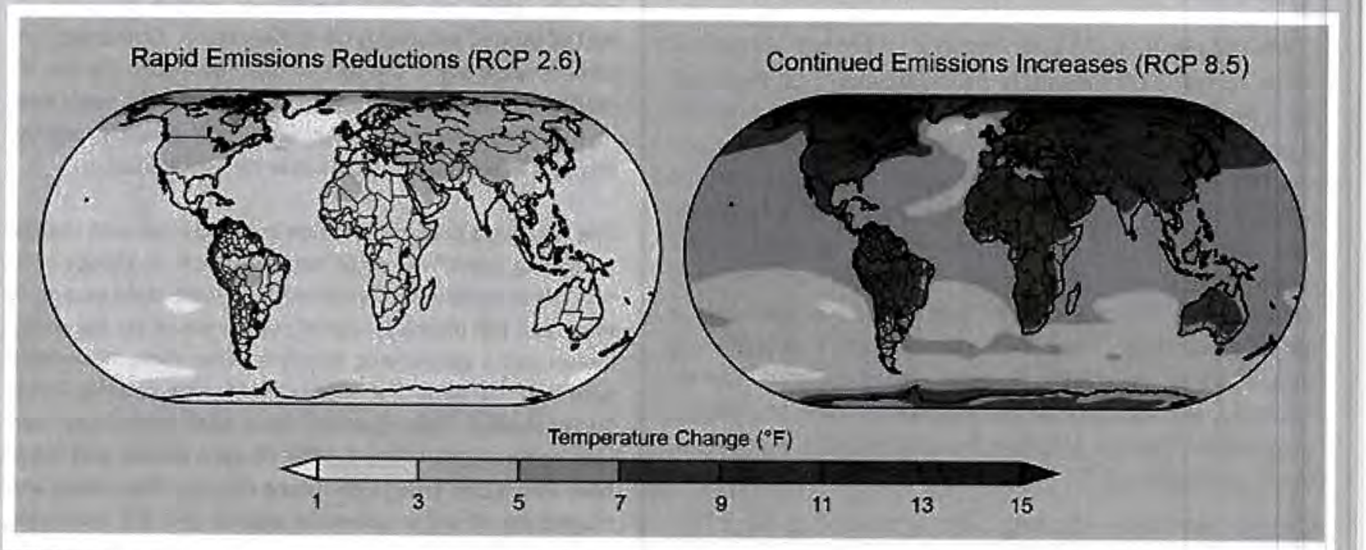

Figure 2.5. Projected change in average annual temperature over the period 2071-2099 (compared to the period 1970-1999) under a low scenario that assumes rapid reductions in emissions and concentrations of heat-trapping gases (RCP 2.6), and a higher scenario that assumes continued increases in emissions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

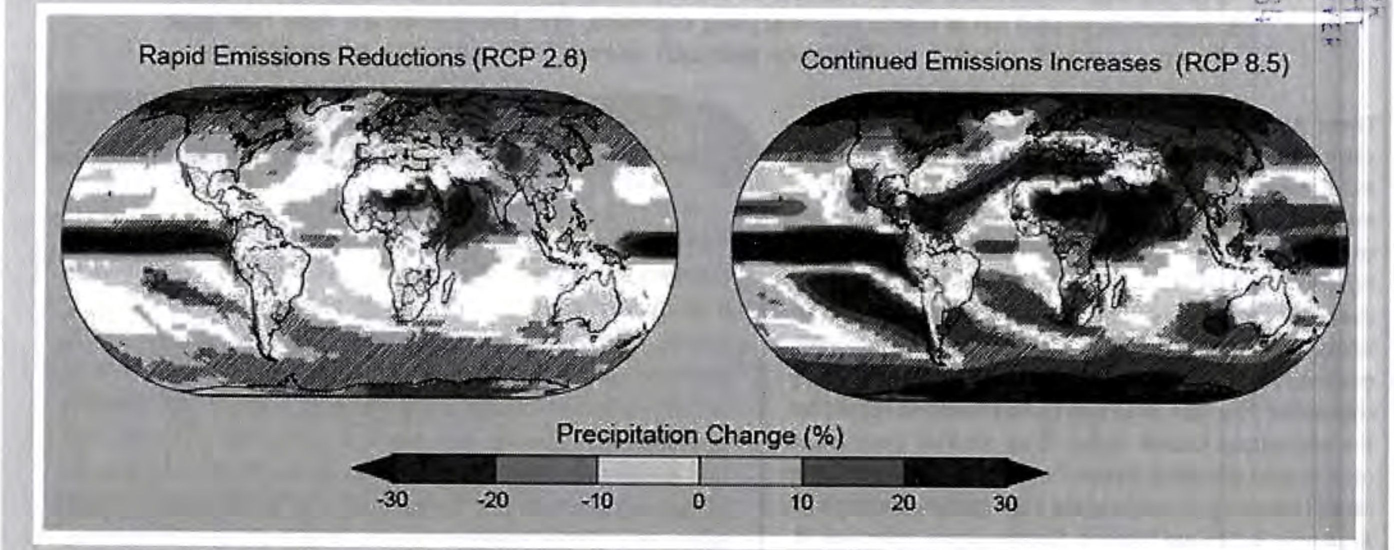

Figure 2.6. Projected change in average annual precipitation over the period 2071-2099 (compared to the period 1970-1999) under a low scenario that assumes rapid reductions in emissions and concentrations of heat-trapping gasses (RCP 2.6), and a higher scenario that assumes continued increases in emissions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

CLIMATE SENSITIVITY

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

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

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

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

Key Message 3: Recent U.S. Temperature Trends

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

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

QUANTIFYING U.S. TEMPERATURE RISE

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

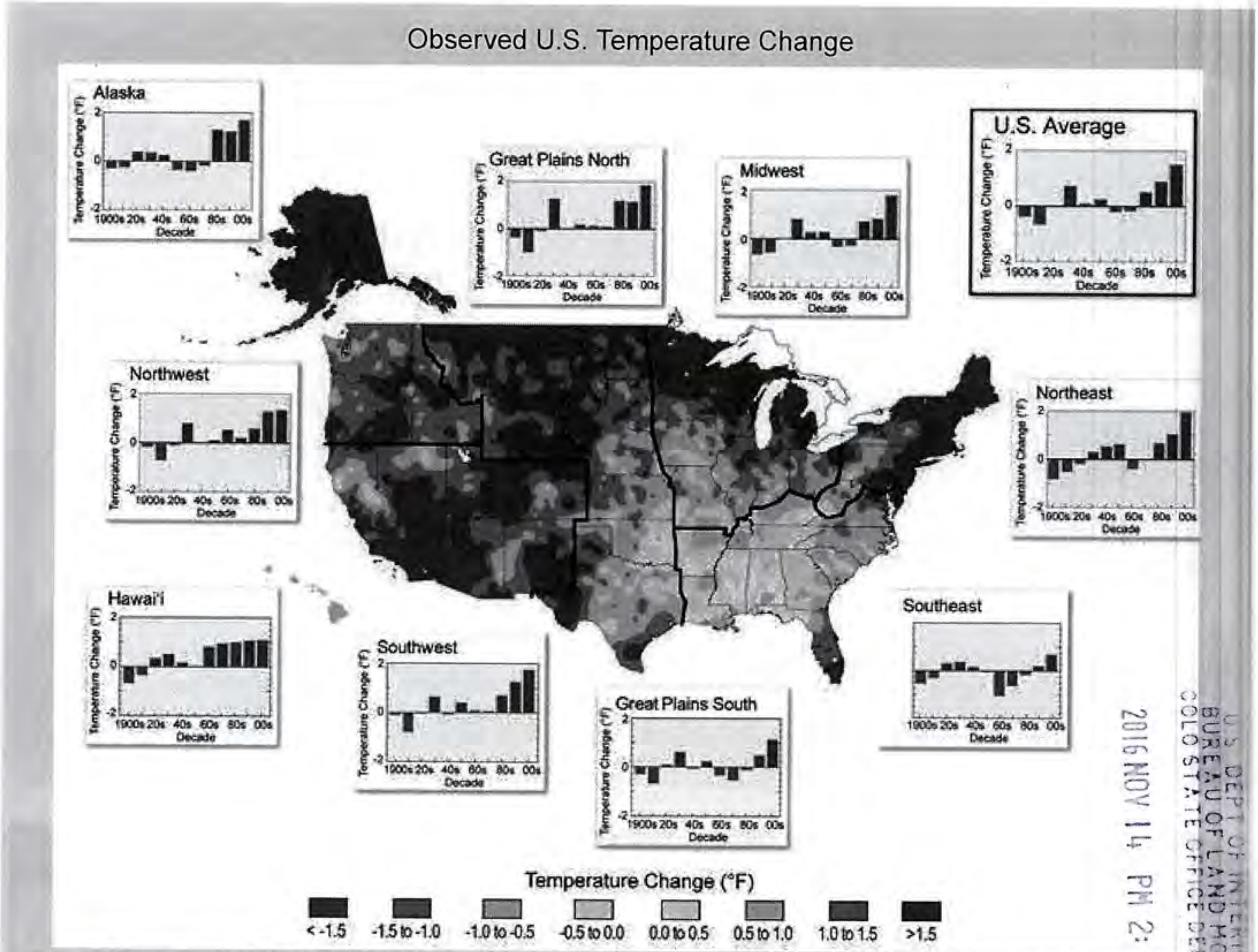

Figure 2.7. The colors on the map show temperature changes over the past 22 years (1991-2012) compared to the 1901-1960 average, and compared to the 1951-1980 average for Alaska and Hawai'i. The bars on the graphs show the average temperature changes by decade for 1901-2012 (relative to the 1901-1960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

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

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

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

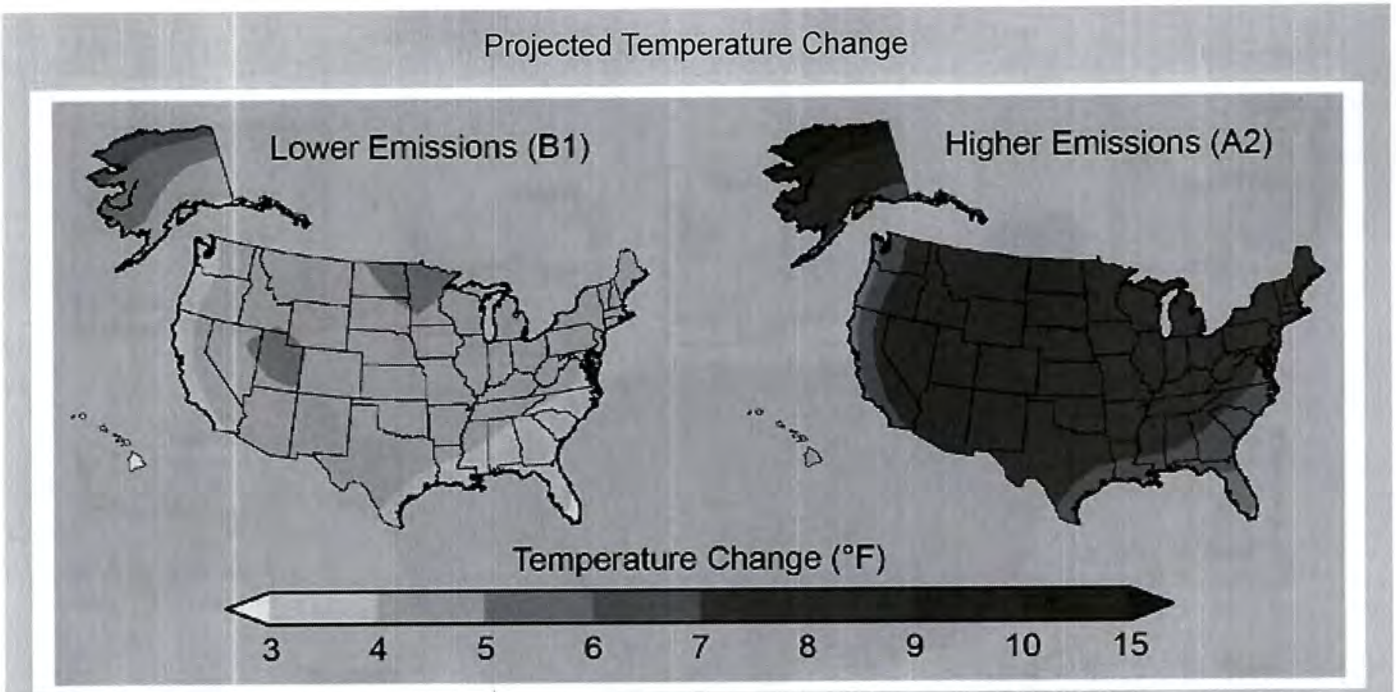

Figure 2.8. Maps show projected change in average surface air temperature in the later part of this century (2071-2099) relative to the later part of the last century (1970-1999) under a scenario that assumes substantial reductions in heat trapping gases (B1, left) and a higher emissions scenario that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

NEWER SIMULATIONS FOR PROJECTED TEMPERATURE (CMIP5 MODELS)

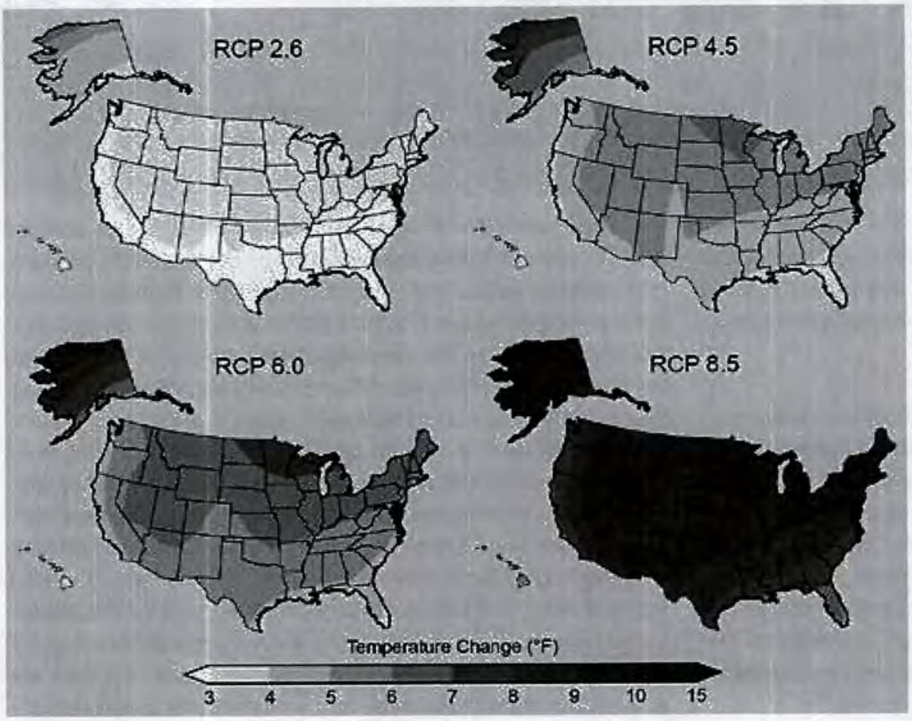

Figure 2.9. The largest uncertainty in projecting climate change beyond the next few decades is the level of heat-trapping gas emissions. The most recent model projections (CMIP5) take into account a wider range of options with regard to human behavior, including a lower scenario than has been considered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

Key Message 4: Lengthening Frost-free Season

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

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

Observed Increase in Frost-Free Season Length

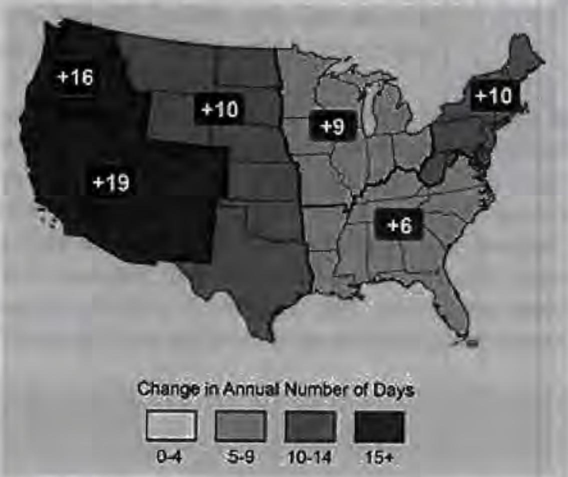

Figure 2.10. The frost-free season length, defined as the period between the last occurrence of 32°F in the spring and the first occurrence of 32°F in the fall, has increased in each U.S. region during 1991-2012 relative to 1901-1960. Increases in frost-free season length correspond to similar increases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

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

In a future in which heat-trapping gas emissions continue to grow, increases of a month or more in the lengths of the frost-free and growing seasons are projected across most of the U.S. by the end of the century, with slightly smaller increases in the northern Great Plains. The largest increases in the frost-free season (more than 8 weeks) are projected for the western U.S., particularly in high elevation and coastal areas. The increases will be con-

Projected Changes in Frost-Free Season Length

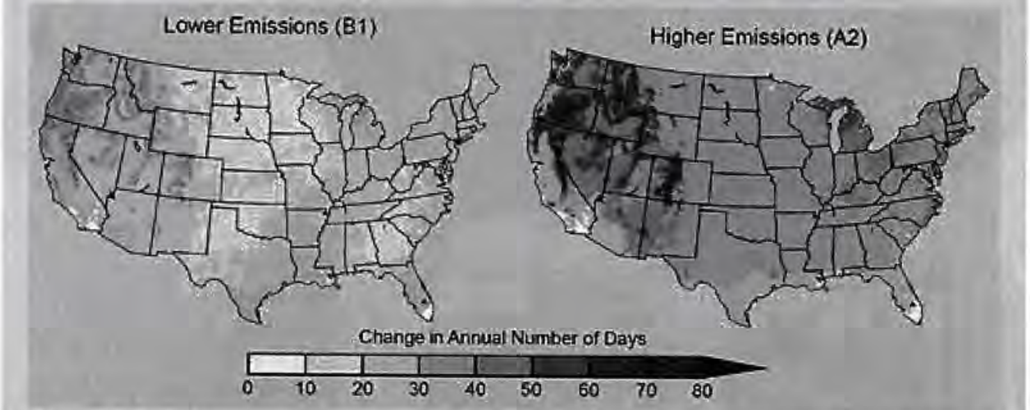

Figure 2.11. The maps show projected increases in frost-free season length for the last three decades of this century (2070-2099 as compared to 1971-2000) under two emissions scenarios, one in which heat-trapping gas emissions continue to grow (A2) and one in which emissions peak in 2050 (B1). Increases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

siderably smaller if heat-trapping gas emissions are reduced, although still substantial. These increases are projected to be much greater than the normal year-to-year variability experienced today. The projected changes also imply that the southern boundary of the seasonal freeze zone will move northward, with increasing frequencies of years without subfreezing temperatures in the most southern parts of the United States.

Key Message 5: U.S. Precipitation Change

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

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

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

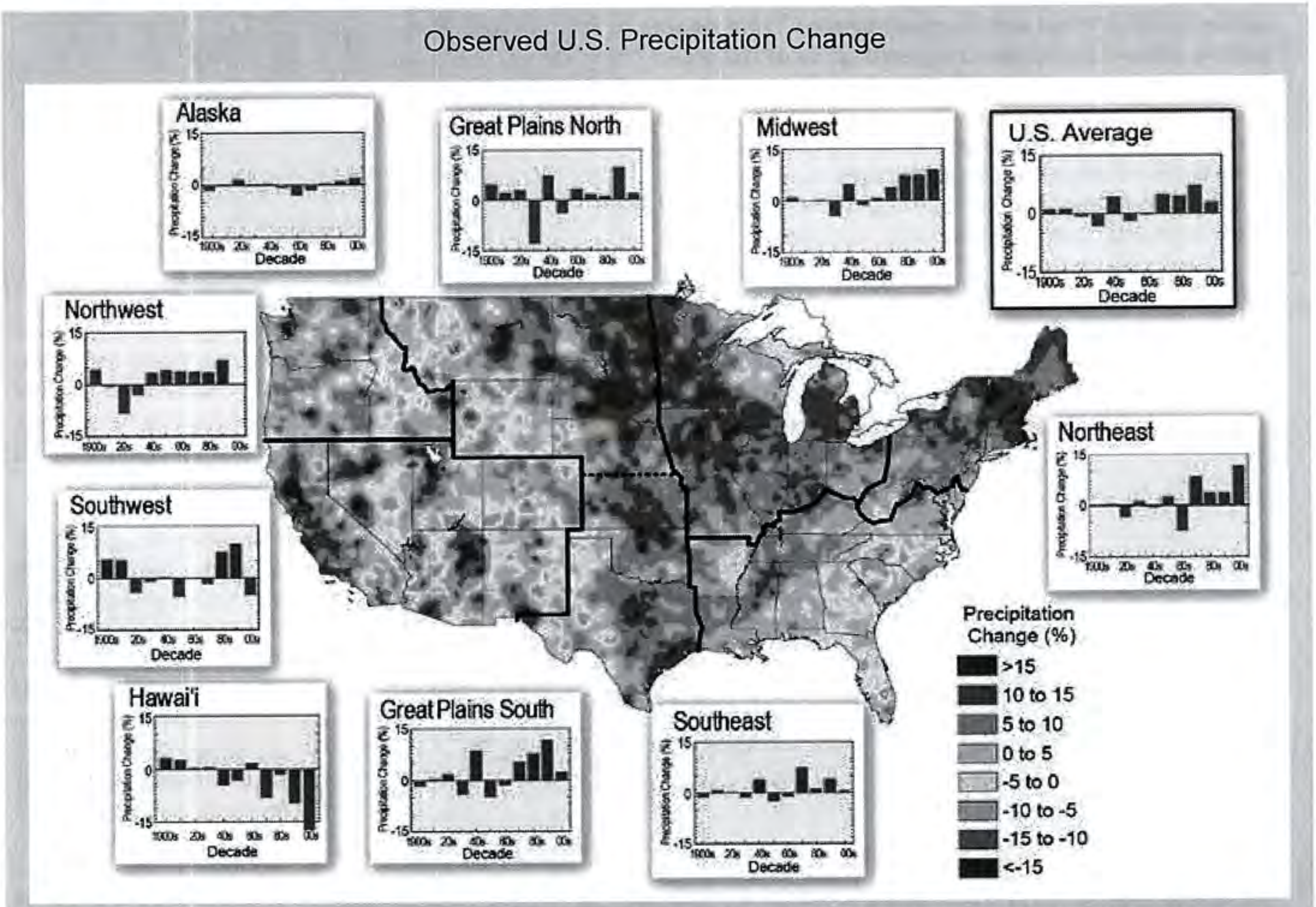

Figure 2.12. The colors on the map show annual total precipitation changes for 1991-2012 compared to the 1901-1960 average, and show wetter conditions in most areas. The bars on the graphs show average precipitation differences by decade for 1901-2012 (relative to the 1901-1960 average) for each region.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

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

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

UNCERTAINTIES IN REGIONAL PROJECTIONS

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

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

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

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

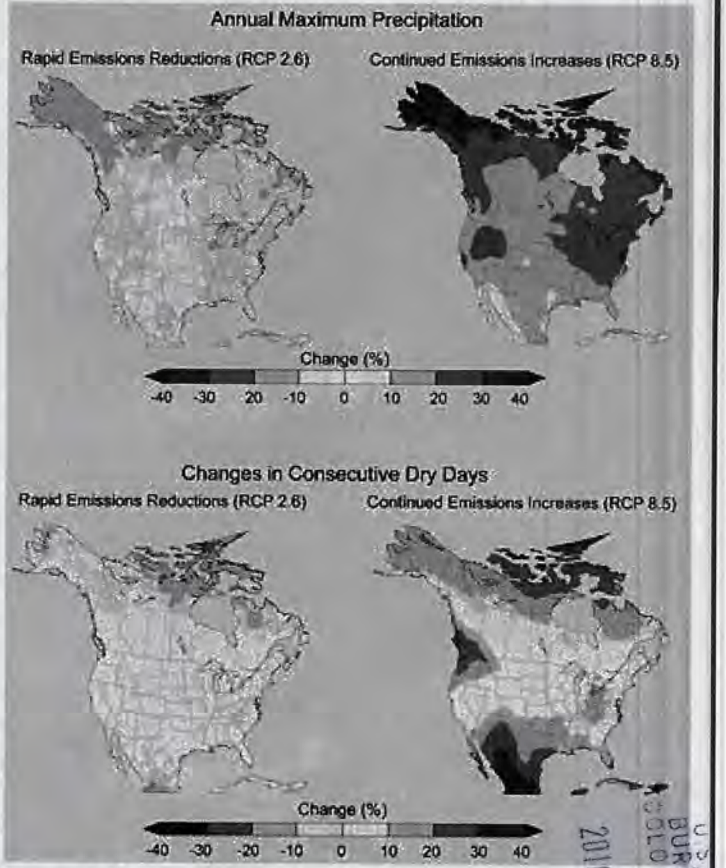

Figure 2.13. Top panels show simulated changes in the average amount of precipitation falling on the wettest day of the year for the period 2070-2099 as compared to 1971-2000 under a scenario that assumes rapid reductions in emissions (RCP 2.6) and one that assumes continued emissions increases (RCP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

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

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

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

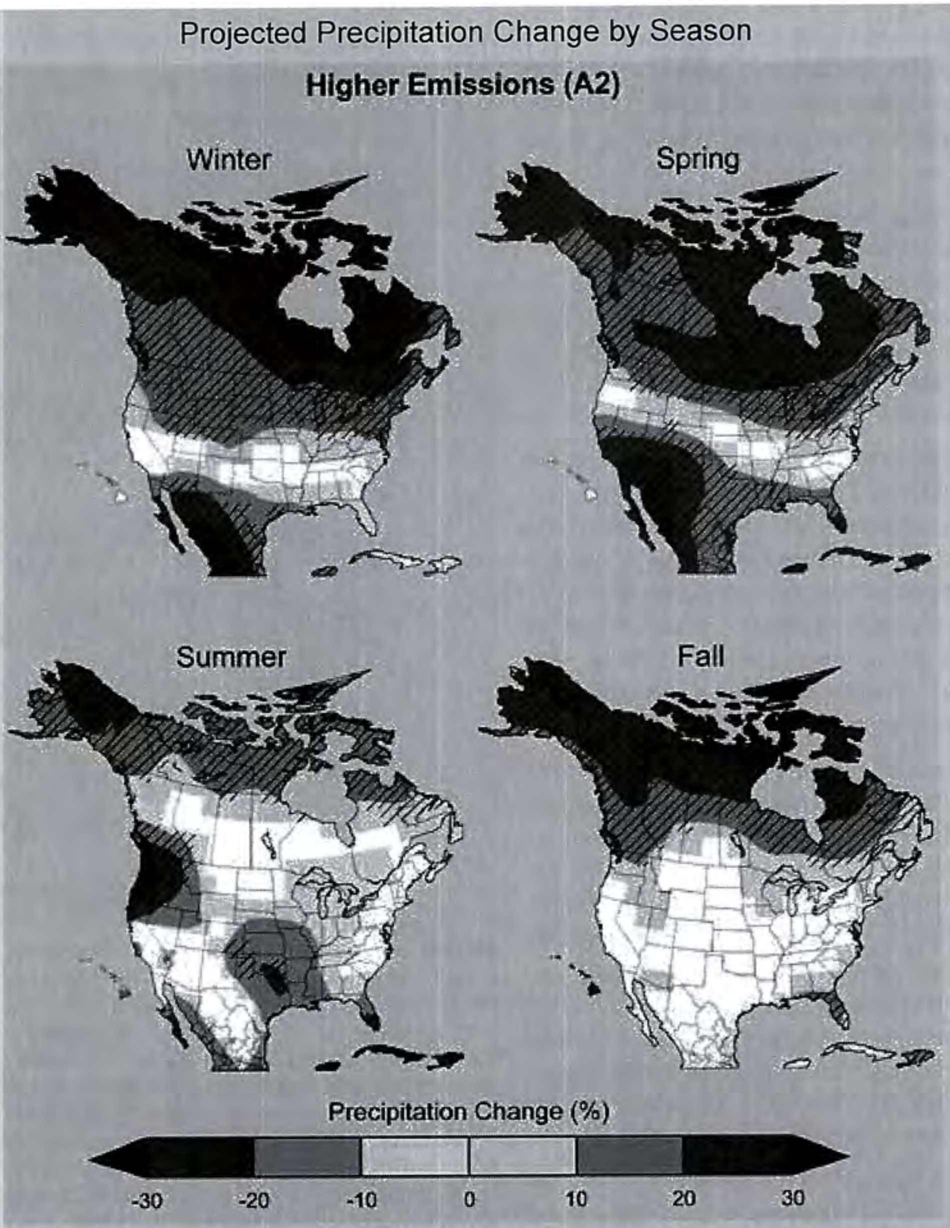

Figure 2.14. Projected change in seasonal precipitation for 2071-2099 (compared to 1970-1999) under an emissions scenario that assumes continued increases in emissions (A2). Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate that the changes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

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

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

NEWER SIMULATIONS FOR PROJECTED PRECIPITATION CHANGE (CMIP5 MODELS)

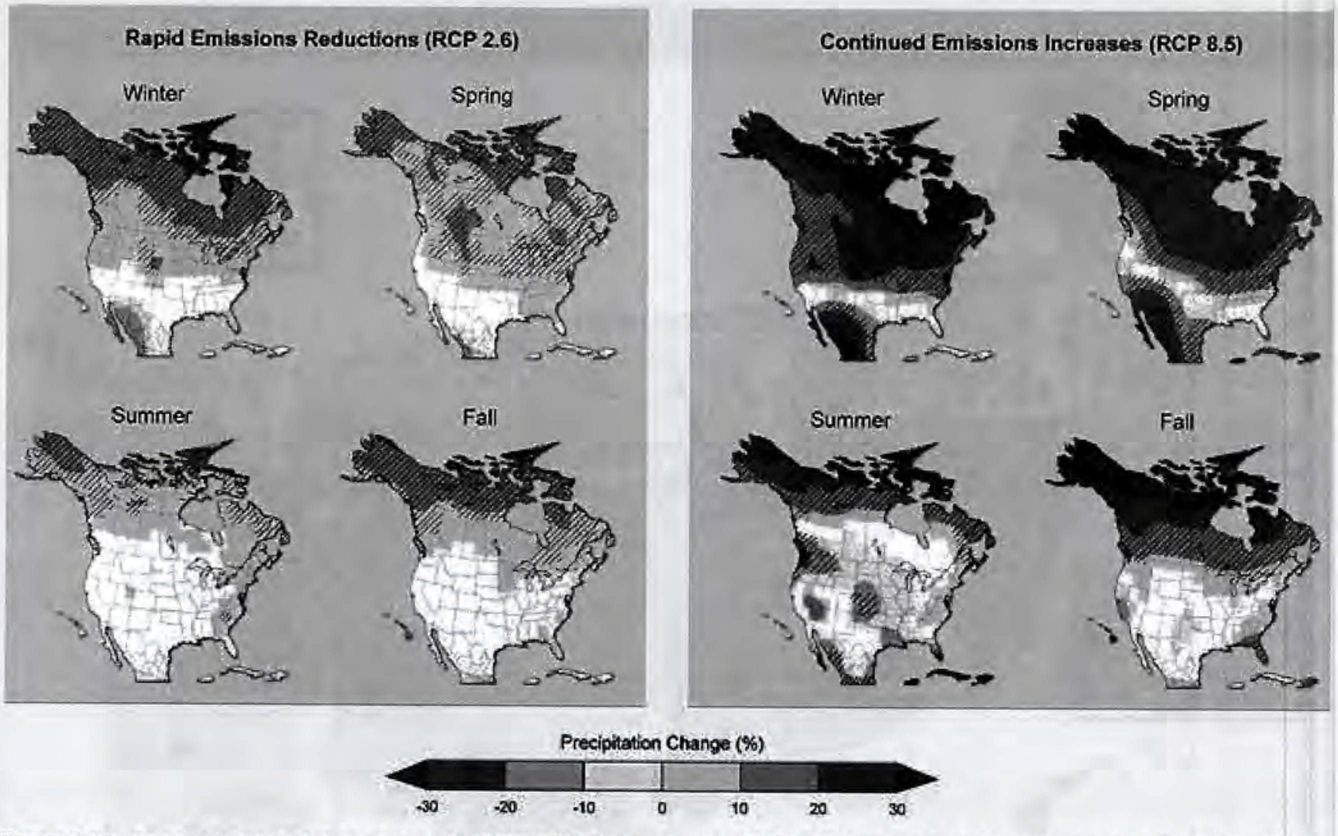

Figure 2.15. Seasonal precipitation change for 2071-2099 (compared to 1970-1999) as projected by recent simulations that include a wider range of scenarios. The maps on the left (RCP 2.6) assume rapid reductions in emissions – more than 70% cuts from current levels by 2050 – and a corresponding much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

Key Message 6: Heavy Downpours Increasing

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

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

Observed U.S. Trend in Heavy Precipitation

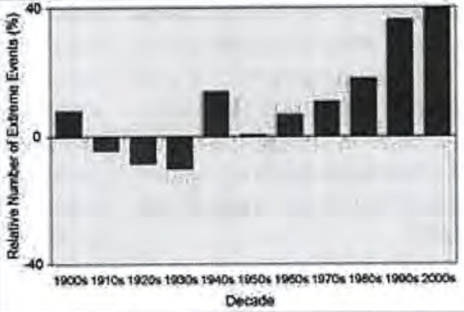

Figure 2.16: One measure of a heavy precipitation event is a 2-day precipitation total that is exceeded on average only once in a five-year period, also known as a once-in-five-year event. As this extreme precipitation index for 1901-2012 shows, the occurrence of such events has become much more common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

Observed Change in Very Heavy Precipitation

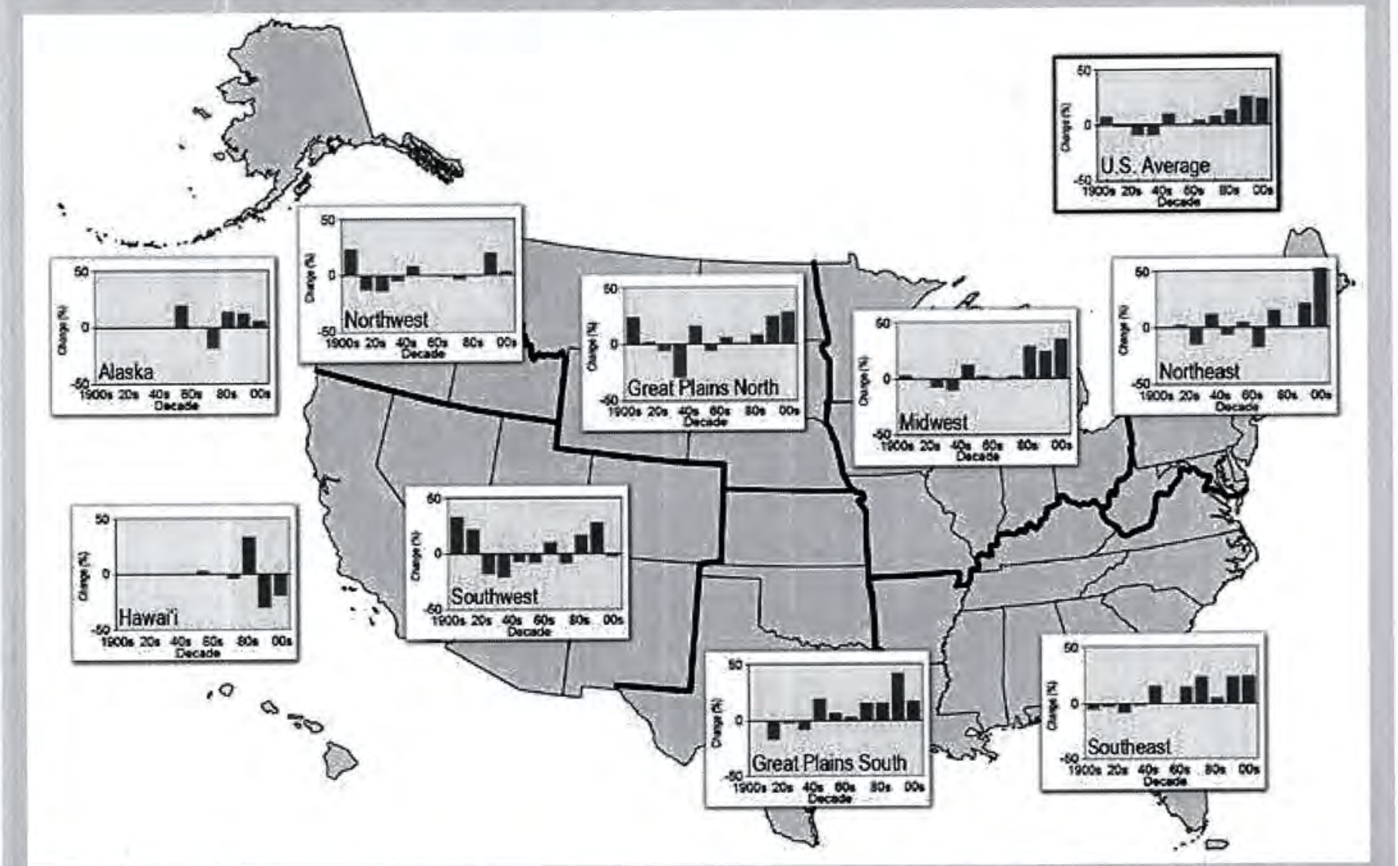

Figure 2.17. Percent changes in the annual amount of precipitation falling in very heavy events, defined as the heaviest 1% of all daily events from 1901 to 2012 for each region. The far right bar is for 2001-2012. In recent decades there have been increases nationally, with the largest increases in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

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

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


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Observed Change in Very Heavy Precipitation

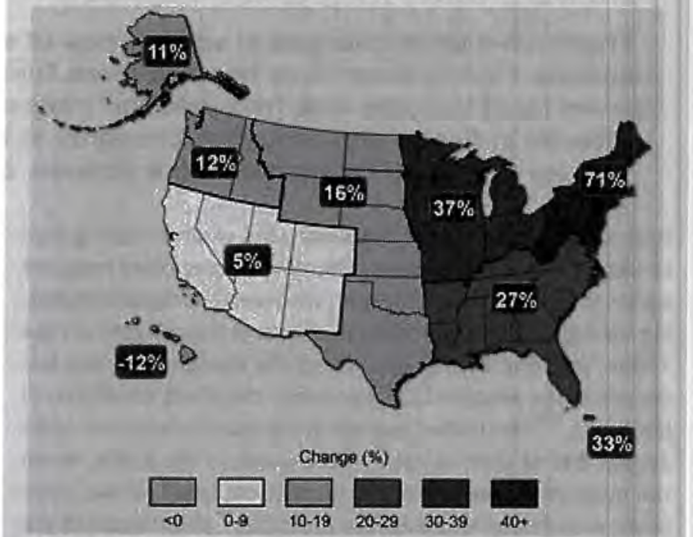

Figure 2.18. The map shows percent increases in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) from 1958 to 2012 for each region of the continental United States. These trends are larger than natural variations for the Northeast, Midwest, Puerto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

Projected Change in Heavy Precipitation Events

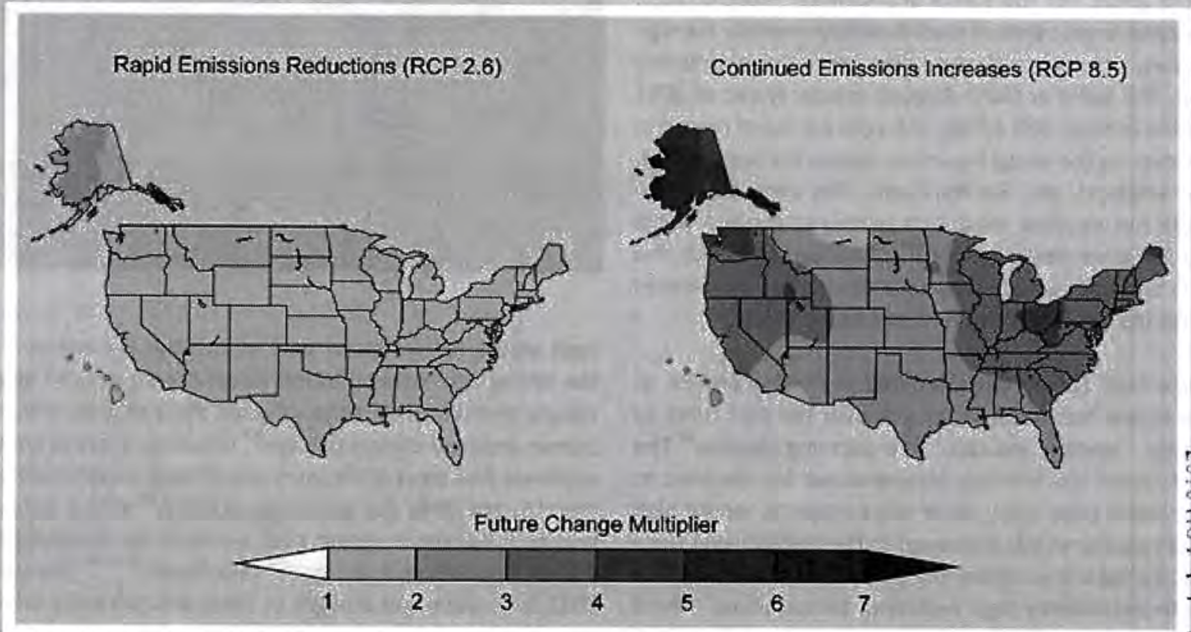

Figure 2.19. Maps show the increase in frequency of extreme daily precipitation events (a daily amount that now occurs once in 20 years) by the later part of this century (2081-2100) compared to the later part of last century (1981-2000). Such extreme events are projected to occur more frequently everywhere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

Key Message 7: Extreme Weather

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

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

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

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

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

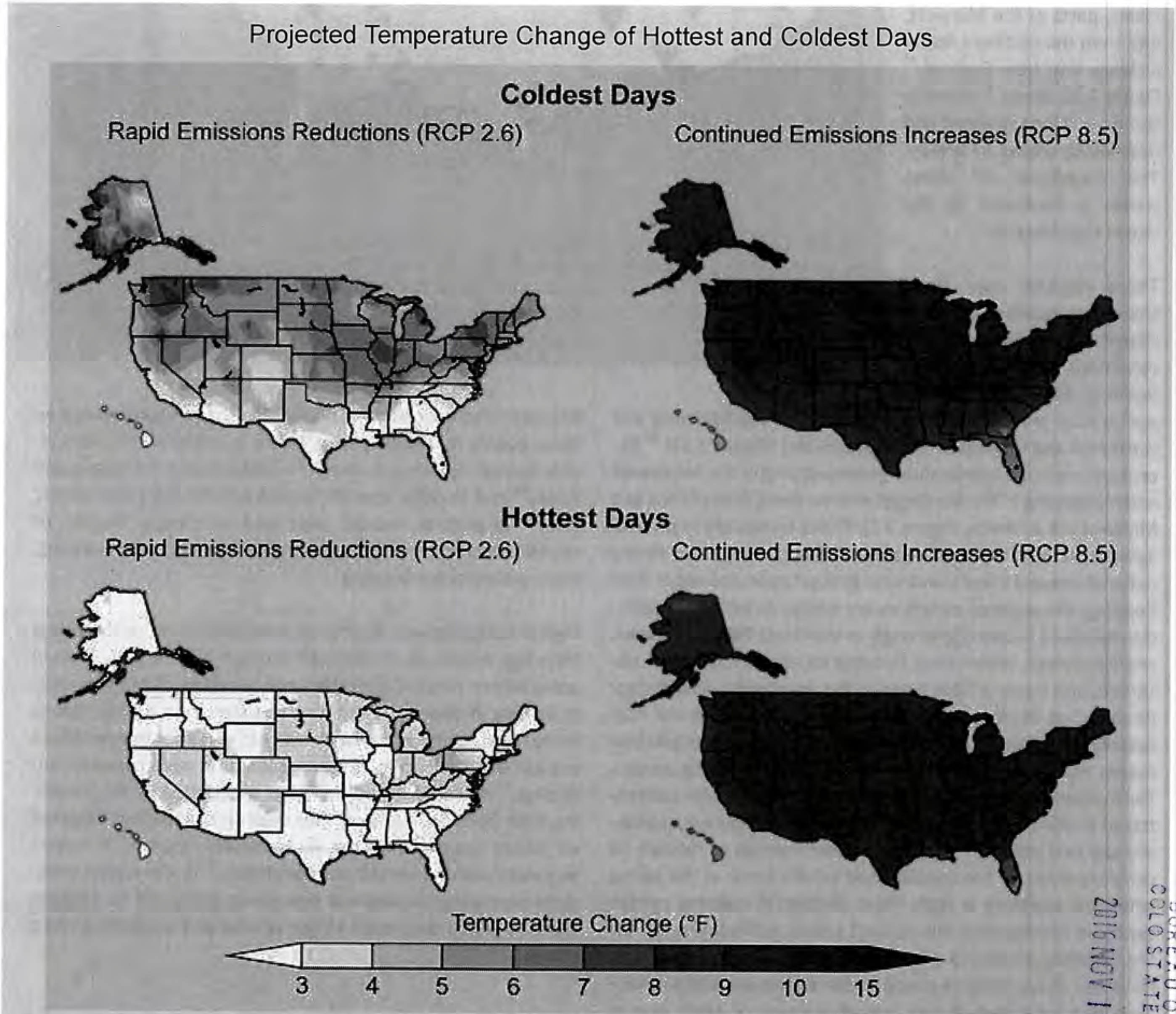

Figure 2.20. Change in surface air temperature at the end of this century (2081-2100) relative to the turn of the last century (1986-2005) on the coldest and hottest days under a scenario that assumes a rapid reduction in heat trapping gases (RCP 2.6) and a scenario that assumes continued increases in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

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

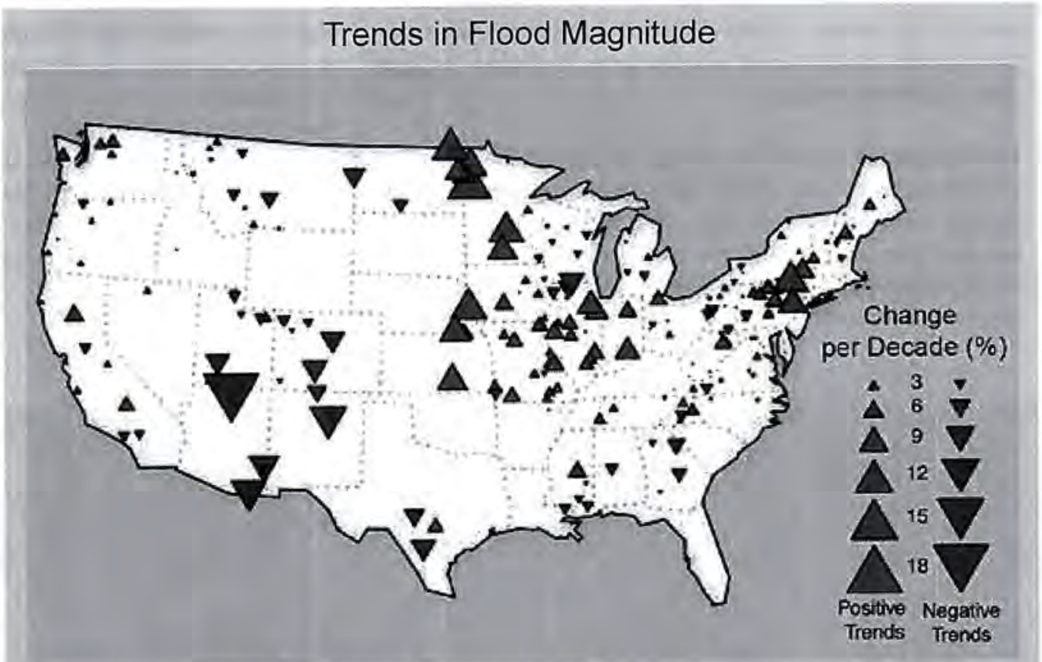
Trends in Flood Magnitude

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

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

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

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

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

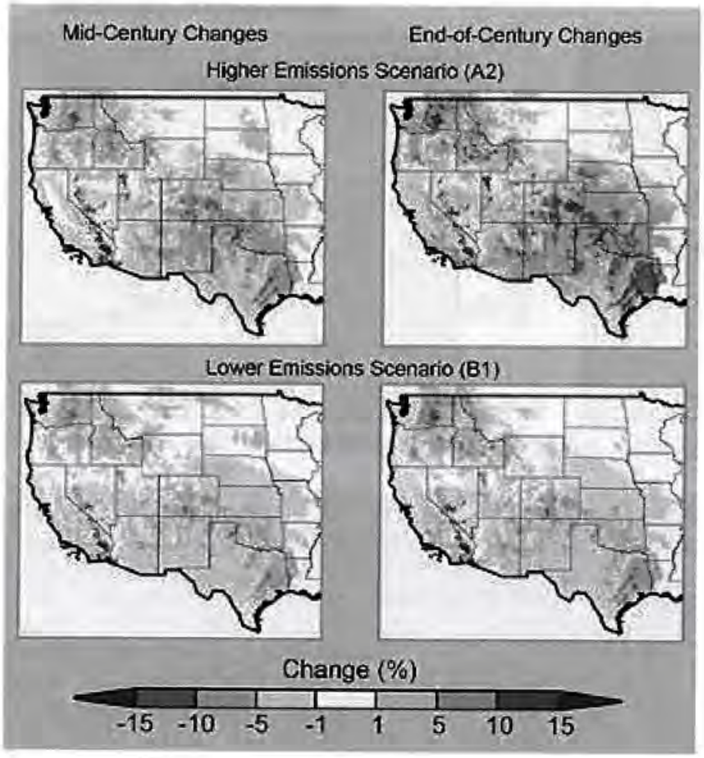

Figure 2.22. Average change in soil moisture compared to 1971-2000, as projected for the middle of this century (2041-2070) and late this century (2071-2100) under two emissions scenarios, a lower scenario (B1) and a higher scenario (A2).[75,77] The future drying of soils in most areas simulated by this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

Key Message 8: Changes in Hurricanes

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

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

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

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

Observed Trends in Hurricane Power Dissipation

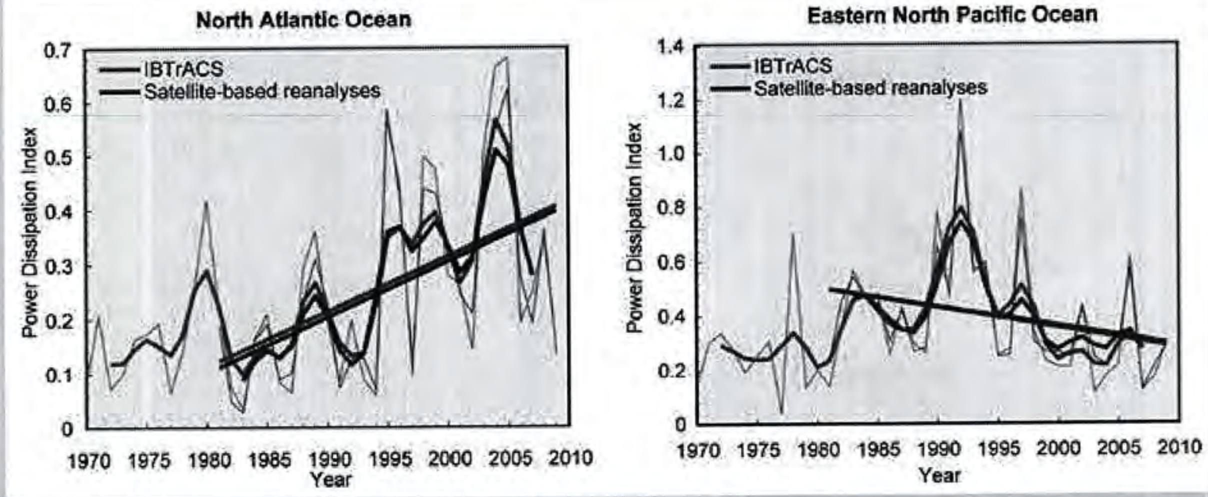

Figure 2.23. Recent variations of the Power Dissipation Index (PDI) in the North Atlantic and eastern North Pacific Oceans. PDI is an aggregate of storm intensity, frequency, and duration and provides a measure of total hurricane power over a hurricane season. There is a strong upward trend in Atlantic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

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

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

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

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

Key Message 9: Changes in Storms

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

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

Severe Convective Storms

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

Winter Storms

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

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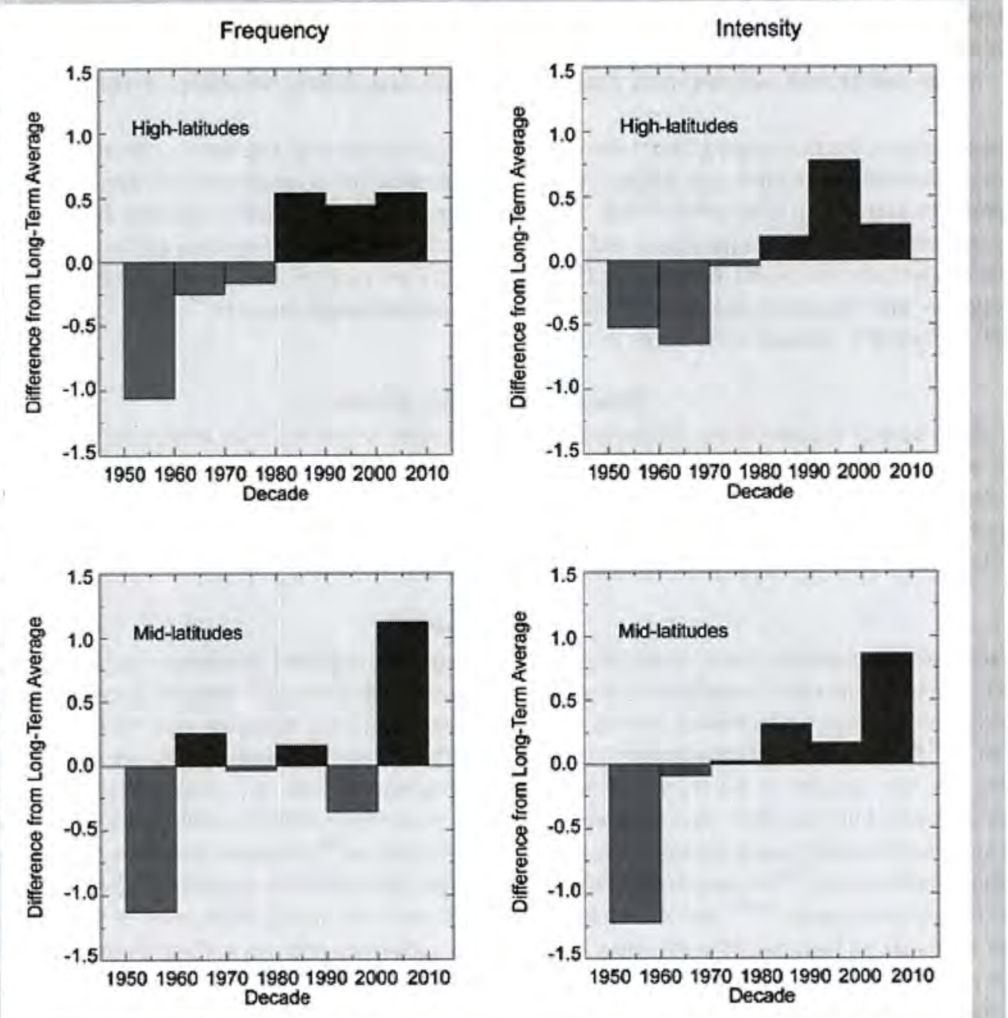
Variation of Storm Frequency and Intensity during the Cold Season (November – March)

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

Key Message 10: Sea Level Rise

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

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

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

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

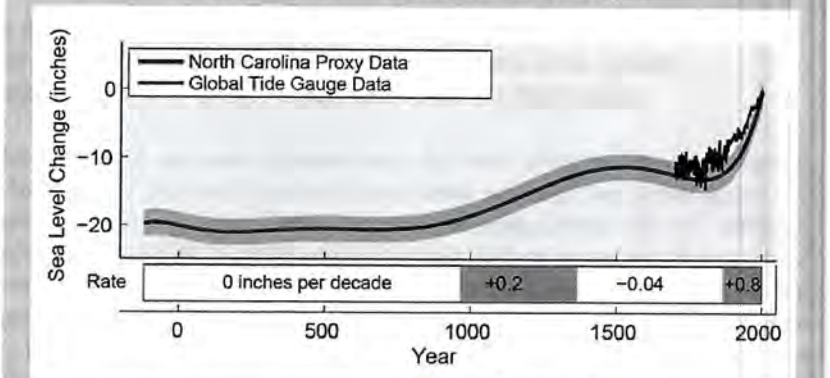
North Atlantic Sea Level Change

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

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

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

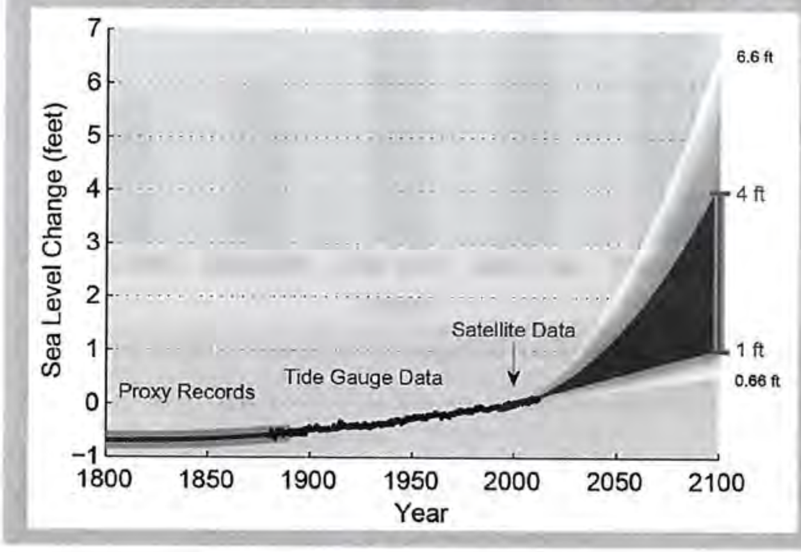
Past and Projected Changes in Global Sea Level Rise

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

Key Message 11: Melting Ice

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

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

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

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

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

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

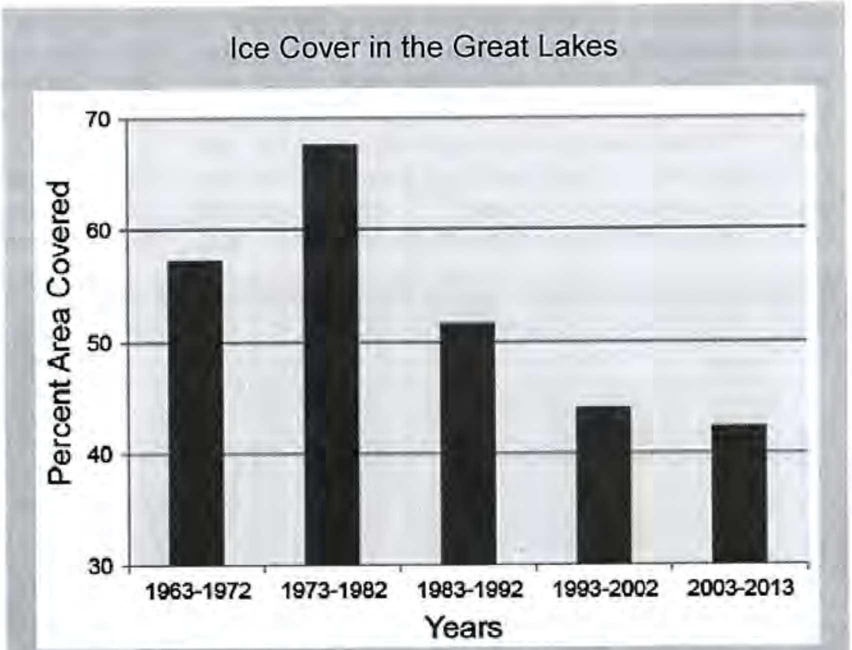

Figure 2.27. Bars show decade averages of annual maximum Great Lakes ice coverage from the winter of 1962-1963, when reliable coverage of the entire Great Lakes began, to the winter of 2012-2013. Bar labels indicate the end year of the winter; for example, 1963-1972 indicates the winter of 1962-1963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

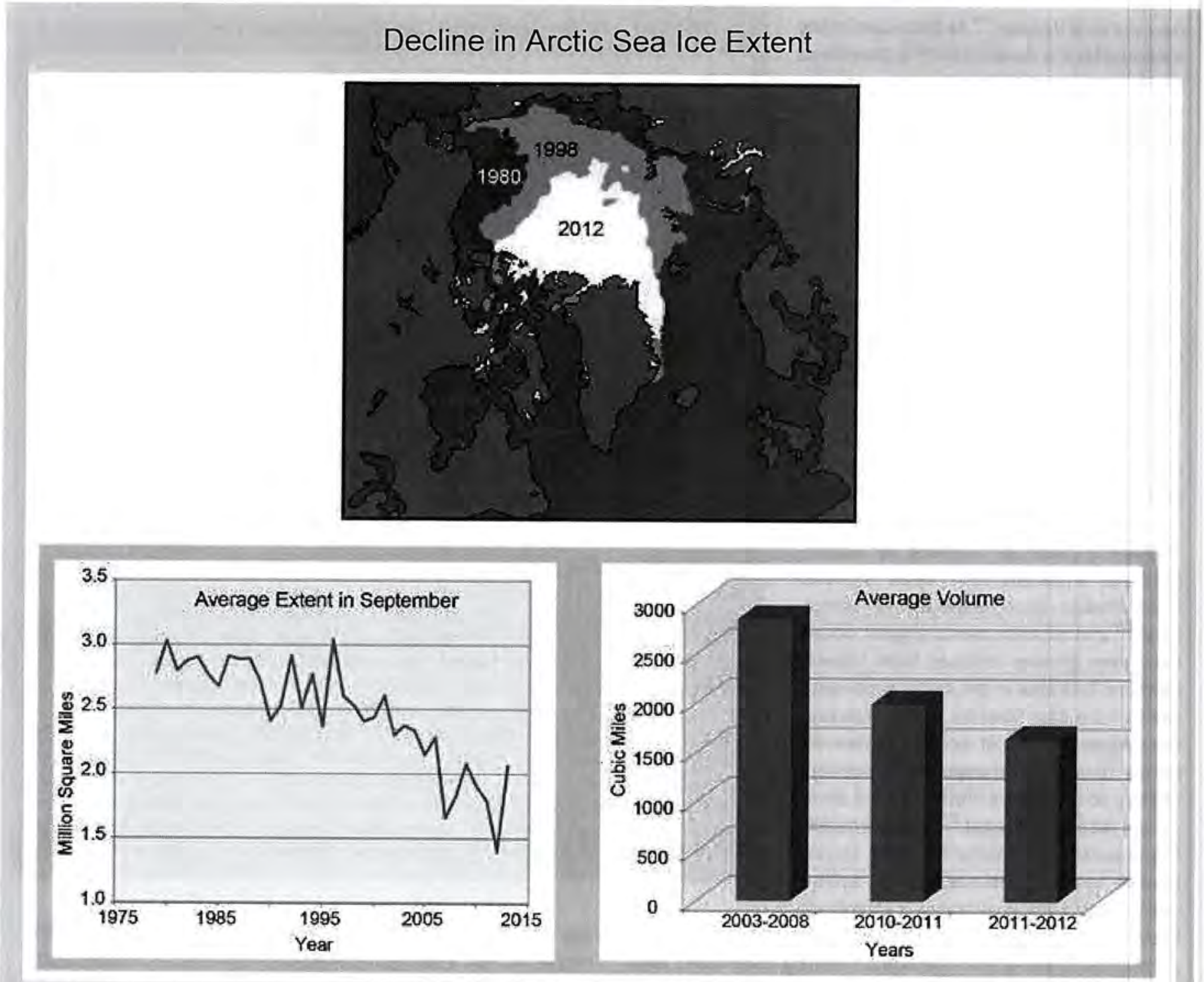

Figure 2.28. Summer Arctic sea ice has declined dramatically since satellites began measuring it in 1979. The extent of sea ice in September 2012, shown in white in the top figure, was more than 40% below the median for 1979-2000. The graph on the bottom left shows annual variations in September Arctic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

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

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

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

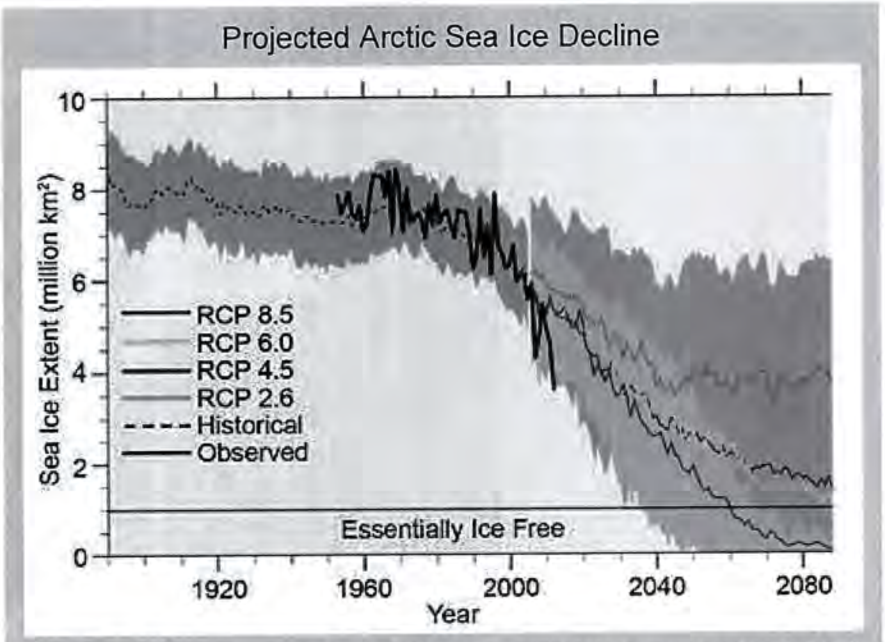

Figure 2.29. Model simulations of Arctic sea ice extent for September (1900-2100) based on observed concentrations of heat-trapping gases and particles (through 2005) and four scenarios. Colored lines for RCP scenarios are model averages (CMIP5) and lighter shades of the line colors denote ranges among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

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

Key Message 12: Ocean Acidification

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

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

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

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

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

As Oceans Absorb CO_2, They Become More Acidic

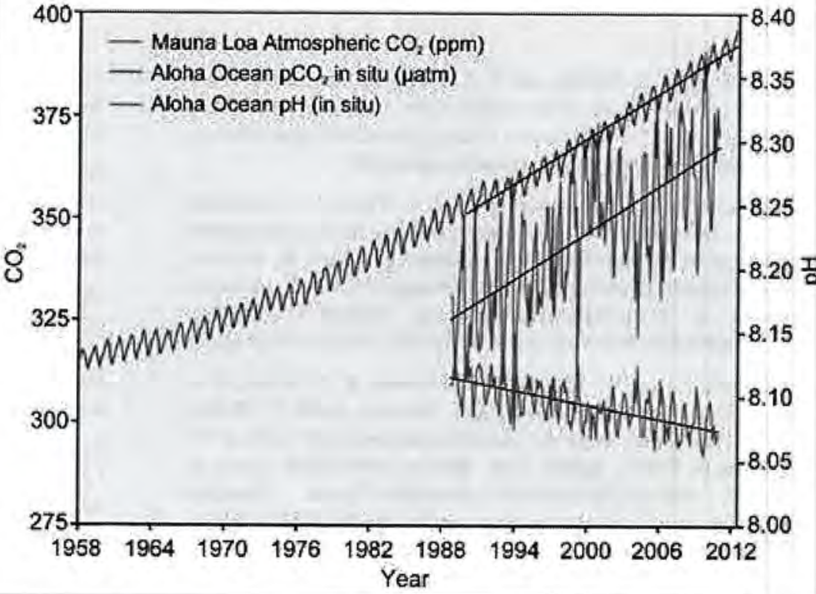

Figure 2.30. The correlation between rising levels of CO_2 in the atmosphere (red) at Mauna Loa and rising CO_2 levels (blue) and falling pH (green) in the nearby ocean at Station Aloha. As CO_2 accumulates in the ocean, the water becomes more acidic (the pH declines). (Figure source: modified from Feely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

Shells Dissolve in Acidified Ocean Water

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

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

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

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

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

KEY MESSAGE #1 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

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

New information and remaining uncertainties

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

Assessment of confidence based on evidence

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

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

KEY MESSAGE #2 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

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

New information and remaining uncertainties

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

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

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

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

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

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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

Assessment of confidence based on evidence

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

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

KEY MESSAGE #3 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

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

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

New information and remaining uncertainties

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

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

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

Assessment of confidence based on evidence

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

KEY MESSAGE #4 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

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

New information and remaining uncertainties

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

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

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

Assessment of confidence based on evidence

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

KEY MESSAGE #5 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

New information and remaining uncertainties

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

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

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

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

Assessment of confidence based on evidence

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

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

KEY MESSAGE #6 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

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

New information and remaining uncertainties

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

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

Assessment of confidence based on evidence

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

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

KEY MESSAGE #7 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

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

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

New information and remaining uncertainties

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

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

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

Assessment of confidence based on evidence

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

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

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

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

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

KEY MESSAGE #8 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

New information and remaining uncertainties

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

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

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

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

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

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

KEY MESSAGE #9 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

New information and remaining uncertainties

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

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

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

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

KEY MESSAGE #10 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

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

New information and remaining uncertainties

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

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

Assessment of confidence based on evidence

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

KEY MESSAGE #11 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

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

New information and remaining uncertainties

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

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

Assessment of confidence based on evidence

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

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

KEY MESSAGE #12 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

New information and remaining uncertainties

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

Assessment of confidence based on evidence

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

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

SECTORS

Cherry farmers in Michigan, insurance agents in Florida, and water managers in Arizona are among the millions of Americans already living with – and adapting to – a range of climate change impacts. Higher temperatures, rising sea levels, and more extreme precipitation events are altering the work of first responders, city planners, engineers, and others, influencing economic sectors from coast to coast. Agriculture, energy, transportation, and more, are all affected by climate change in concrete ways. American communities are contending with these changes now, and will be doing so increasingly in the future.

Sectors of our economy do not exist in isolation. Forest management activities, for example, affect and are affected by water supply, changing ecosystems, impacts to biological diversity, and energy availability. Water supply and energy use are completely intertwined, since water is used to generate energy, and energy is required to pump, treat, and deliver water – which means that irrigation-dependent farmers and urban dwellers are linked as well. Human health is affected by water supply, agricultural practices, transportation systems, energy availability, and land use, among other factors – touching the lives of patients, nurses, county health administrators, and many others. Human social systems and communities are directly affected by extreme weather events and changes in natural resources such as water availability and quality; they are also affected both directly and indirectly by ecosystem health.

This report addresses some of these topics individually, focusing on the climate-related risks and opportunities that occur within individual sectors, while others take a cross-sector approach. Single-sector chapters focus on:

- Water resources
- Energy production and use
- Transportation
- Agriculture
- Forests
- Human health
- Ecosystems and biodiversity

Six crosscutting chapters address how climate change interacts with multiple sectors. These cover the following topics:

- Energy, water, and land use
- Urban infrastructure and vulnerability
- Indigenous peoples, lands, and resources
- Land use and land cover
- Rural communities
- Biogeochemical cycles

A common theme is that these sectors are interconnected in many ways. These intricate connections mean that changes in one sector are often amplified or reduced through links to other sectors. Another theme is how decisions can influence a cascade of events that affect individual and national vulnerability and/or resiliency to climate change across multiple sectors. This "systems approach" helps to reveal, for example, how adaptation and mitigation strategies are part of dynamic and interrelated systems. In this way, for example, adaptation plans for future coastal infrastructure are connected with the kinds of mitigation strategies that are – or are not – put into place today, since the amount of future sea level rise will differ according to various societal decisions about current and future emissions. These chapters also address the importance of underlying vulnerabilities and the ways they may influence risks associated with climate change.

The chapters in the following section assess risks in the selected sectors, and include both observations of existing impacts associated with climate change, as well as projected impacts over the next several decades and beyond.

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Climate Change Impacts in the United States

CHAPTER 3
WATER RESOURCES

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On the Web: http://nca2014.globalchange.gov/report/sectors/water

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3 WATER RESOURCES

KEY MESSAGES


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Climate Change Impacts on the Water Cycle

1. **Annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions. Very heavy precipitation events have increased nationally and are projected to increase in all regions. The length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States.**

2. **Short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast.**

3. **Flooding may intensify in many U.S. regions, even in areas where total precipitation is projected to decline.**

4. **Climate change is expected to affect water demand, groundwater withdrawals, and aquifer recharge, reducing groundwater availability in some areas.**

5. **Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands.**

6. **Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and other pollutant loads.**

Climate Change Impacts on Water Resources Use and Managment

7. **Climate change affects water demand and the ways water is used within and across regions and economic sectors. The Southwest, Great Plains, and Southeast are particularly vulnerable to changes in water supply and demand.**

8. **Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. These trends are expected to continue, increasing the likelihood of water shortages for many uses.**

9. **Increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the United States.**

Adaptation and Institutional Responses

10. **In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed within existing practices.**

11. **Increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts. Many institutional, scientific, economic, and political barriers present challenges to implementing adaptive strategies.**

This chapter contains three main sections: climate change impacts on the water cycle, climate change impacts on water resources use and management, and adaptation and institutional responses. Key messages for each section are summarized above.

The cycle of life is intricately joined with the cycle of water.

—Jacques-Yves Cousteau

Climate Change Impacts on the Water Cycle

Water cycles constantly from the atmosphere to the land and the oceans (through precipitation and runoff) and back to the atmosphere (through evaporation and the release of water from plant leaves), setting the stage for all life to exist. The water cycle is dynamic and naturally variable, and societies and ecosystems are accustomed to functioning within this variability. However, climate change is altering the water cycle in multiple ways over different time scales and geographic areas, presenting unfamiliar risks and opportunities.

Key Message 1: Changing Rain, Snow, and Runoff

Annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions. Very heavy precipitation events have increased nationally and are projected to increase in all regions. The length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States.

Annual average precipitation over the continental U.S. as a whole increased by close to two inches (0.16 inches per decade) between 1895 and 2011.[1,2] In recent decades, annual average precipitation increases have been observed across the Midwest, Great Plains, the Northeast, and Alaska, while decreases have been observed in Hawai'i and parts of the Southeast and Southwest (Ch. 2: Our Changing Climate, Figure 2.12). Average annual precipitation is projected to increase across the northern U.S., and decrease in the southern U.S., especially the Southwest. (Ch. 2: Our Changing Climate, Figures 2.14 and 2.15).[3]

The number and intensity of very heavy precipitation events (defined as the heaviest 1% of all daily events from 1901 to 2012) have been increasing significantly across most of the United States. The amount of precipitation falling in the heaviest daily events has also increased in most areas of the United States (Ch. 2: Our Changing Climate, Figure 2.17). For example, from 1950 to 2007, daily precipitation totals with 2-, 5-, and 10-year average recurrence periods increased in the Northeast and western Great Lakes.[4] Very heavy precipitation events are projected to increase everywhere (Ch. 2: Our Changing Climate, Figure 2.19).[5] Heavy precipitation events that historically occurred once in 20 years are projected to occur as frequently as every 5 to 15 years by late this century.[6] The number and magnitude of the heaviest precipitation events is projected to increase everywhere in the United States (Ch. 2: Our Changing Climate, Figure 2.13).

Dry spells are also projected to increase in length in most regions, especially in the southern and northwestern portions of the contiguous United States (Ch. 2: Our Changing Climate, Figure 2.13). Projected changes in total average annual precipitation are generally small in many areas, but both wet and dry extremes (heavy precipitation events

Projected Changes in Snow, Runoff, and Soil Moisture

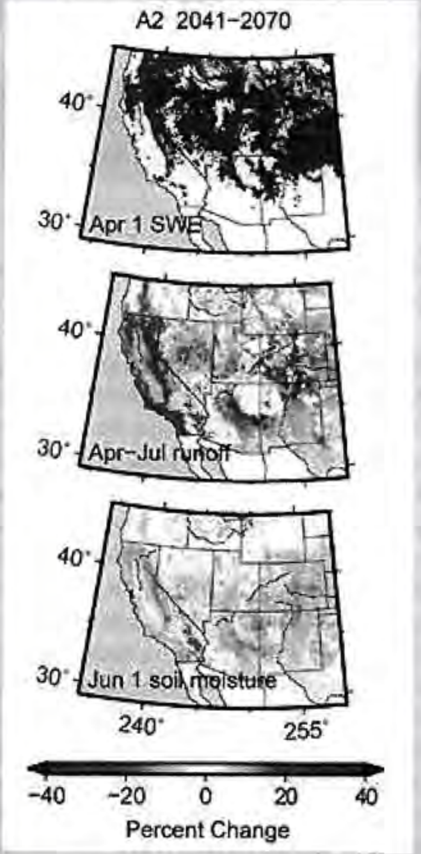


Figure 3.1. These projections, assuming continued increases in heat-trapping gas emissions (A2 scenario; Ch. 2: Our Changing Climate), illustrate: a) major losses in the water content of the snowpack that fills western rivers (snow water equivalent, or SWE); b) significant reductions in runoff in California, Arizona, and the central Rocky Mountains; and c) reductions in soil moisture across the Southwest. The changes shown are for mid-century (2041-2070) as percentage changes from 1971-2000 conditions (Figure source: Cayan et al. 2013[18]).

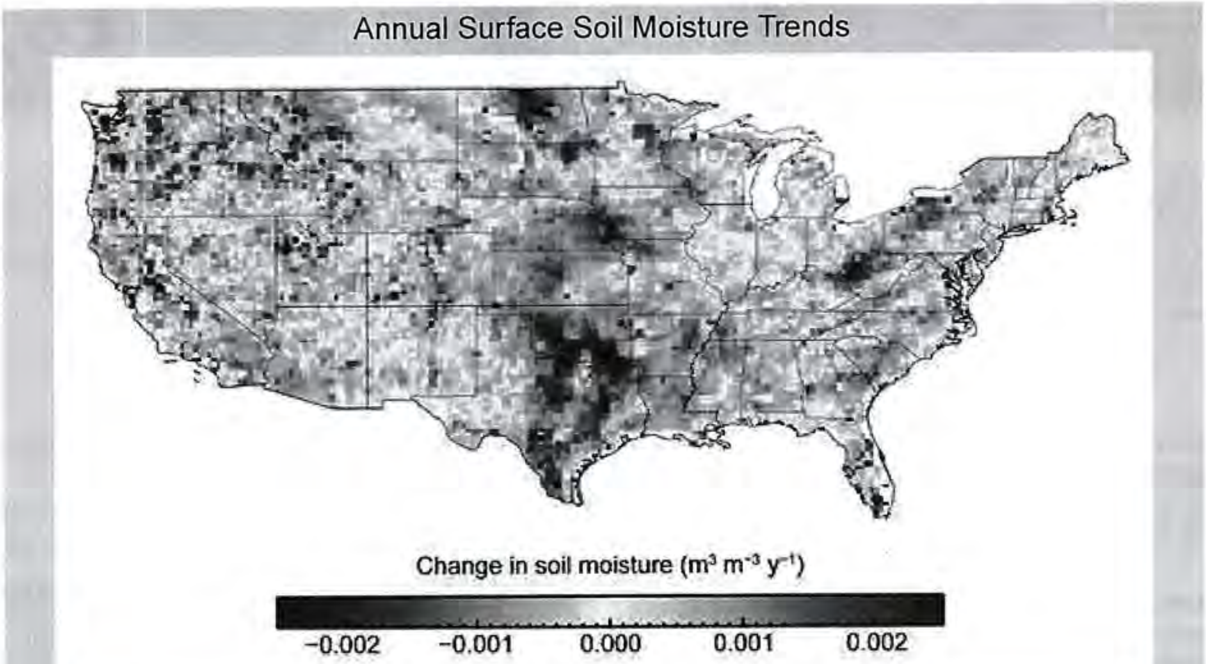


Figure 3.2. Changes in annual surface soil moisture per year over the period 1988 to 2010 based on multi-satellite datasets. Surface soil moisture exhibits wetting trends in the Northeast, Florida, upper Midwest, and Northwest, and drying trends almost everywhere else. (Images provided by W. Dorigo[35]).

and length of dry spells) are projected to increase substantially almost everywhere.

The timing of peak river levels has changed in response to warming trends. Snowpack and snowmelt-fed rivers in much of the western U.S. have earlier peak flow trends since the middle of the last century, including the past decade (Ch. 2: Our Changing Climate).[7,8] This is related to declines in spring snowpack, earlier snowmelt-fed streamflow, and larger percentages of precipitation falling as rain instead of snow. These changes have taken place in the midst of considerable year-to-year variability and long-term natural fluctuations of the western U.S. climate, as well as other influences, such as the effects of dust and soot on snowpacks.[7,9] There are both natural and human influences on the observed trends.[10,11] However, in studies specifically designed to differentiate between natural and human-induced causes, up to 60% of these changes have been attributed to human-induced climate warming,[10] but only among variables that are more responsive to warming than to precipitation variability, such as the effect of air temperature on snowpack.[12]

Other historical changes related to peak river-flow have been observed in the northern Great Plains, Midwest, and Northeast,[13,14] along with striking reductions in lake ice cover (Ch. 2: Our Changing Climate).[15,16]

Permafrost is thawing in many parts of Alaska, a trend that not only affects habitats and infrastructure but also mobilizes subsurface water and reroutes surface water in ways not previously witnessed.[17] Nationally, all of these trends are projected to become even more pronounced as the climate continues to warm (Figure 3.1).

Evapotranspiration (ET – the evaporation of moisture from soil, on plants and trees, and from water bodies; and transpiration, the use and release of water from plants), is the second largest component of the water cycle after precipitation. ET responds to temperature, solar energy, winds, atmospheric humidity, and moisture availability at the land surface and regulates amounts of soil moisture, groundwater recharge, and runoff.[19] Transpiration comprises between 80% and 90% of total ET on land (Ch. 6: Agriculture).[20] In snowy settings, sublimation of snow and ice (loss of snow and ice directly into water vapor without passing through a liquid stage) can increase these returns of water to the atmosphere, sometimes in significant amounts.[21] These interactions complicate estimation and projection of regional losses of water from the land surface to the atmosphere.

Globally-averaged ET increased between 1982 and 1997 but stopped increasing, or has decreased, since about 1998.[22] In North America, the observed ET decreases occurred in water-rich rather than water-limited areas. Factors contributing to these ET decreases are thought to include decreasing wind

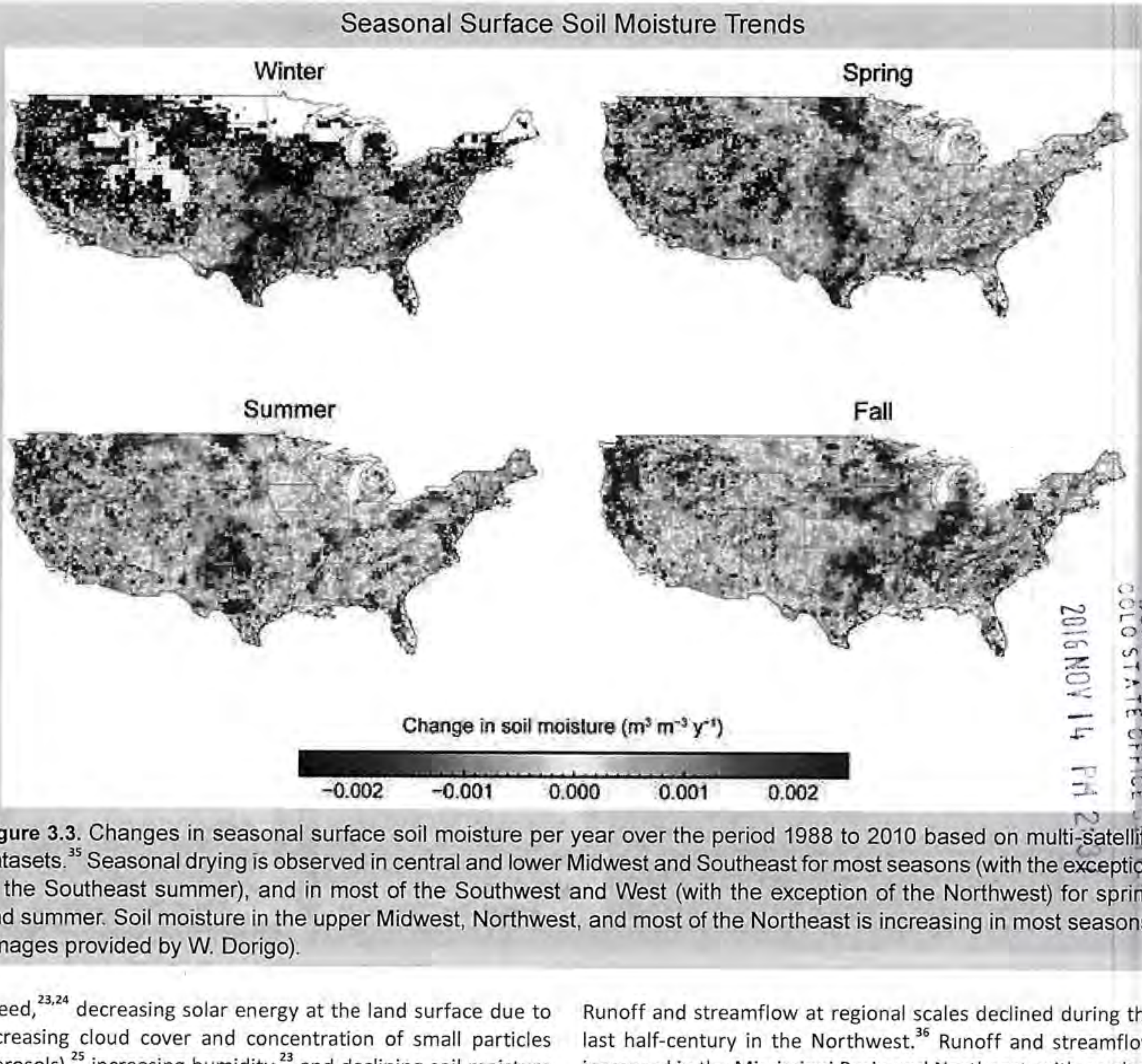


Figure 3.3. Changes in seasonal surface soil moisture per year over the period 1988 to 2010 based on multi-satellite datasets.[35] Seasonal drying is observed in central and lower Midwest and Southeast for most seasons (with the exception of the Southeast summer), and in most of the Southwest and West (with the exception of the Northwest) for spring and summer. Soil moisture in the upper Midwest, Northwest, and most of the Northeast is increasing in most seasons. (Images provided by W. Dorigo).

speed,[23,24] decreasing solar energy at the land surface due to increasing cloud cover and concentration of small particles (aerosols),[25] increasing humidity,[23] and declining soil moisture (Figure 3.2).[26]

Evapotranspiration projections vary by region,[27,28,29,30] but the atmospheric potential for ET is expected to increase; actual ET will be affected by regional soil moisture changes. Much more research is needed to confidently identify historical trends, causes, and implications for future ET trends.[31] This represents a critical uncertainty in projecting the impacts of climate change on regional water cycles.

Soil moisture plays a major role in the water cycle, regulating the exchange of water, energy, and carbon between the land surface and the atmosphere,[22] the production of runoff, and the recharge of groundwater aquifers. Soil moisture is projected to decline with higher temperatures and attendant increases in the potential for ET in much of the country, especially in the Great Plains,[29] Southwest,[18,32,33] and Southeast.[28,34]

Runoff and streamflow at regional scales declined during the last half-century in the Northwest.[36] Runoff and streamflow increased in the Mississippi Basin and Northeast, with no clear trends in much of the rest of the continental U.S.,[37] although a declining trend is emerging in annual runoff in the Colorado River Basin.[38] These changes need to be considered in the context of tree-ring studies in California's Central Valley, the Colorado River and Wind River basins, and the southeastern U.S. that indicate that these regions have experienced prolonged, even drier and wetter conditions at various times in the past two thousand years.[8,39,40] Human-caused climate change, when superimposed on past natural variability, may amplify these past extreme conditions. Projected changes in runoff for eight basins in the Northwest, northern Great Plains, and Southwest are illustrated in Figure 3.4.

Basins in the southwestern U.S. and southern Rockies (for example, the Rio Grande and Colorado River basins) are projected to experience gradual runoff declines during this century. Basins in the Northwest to north-central U.S. (for example, the

Streamflow Projections for River Basins in the Western U.S.

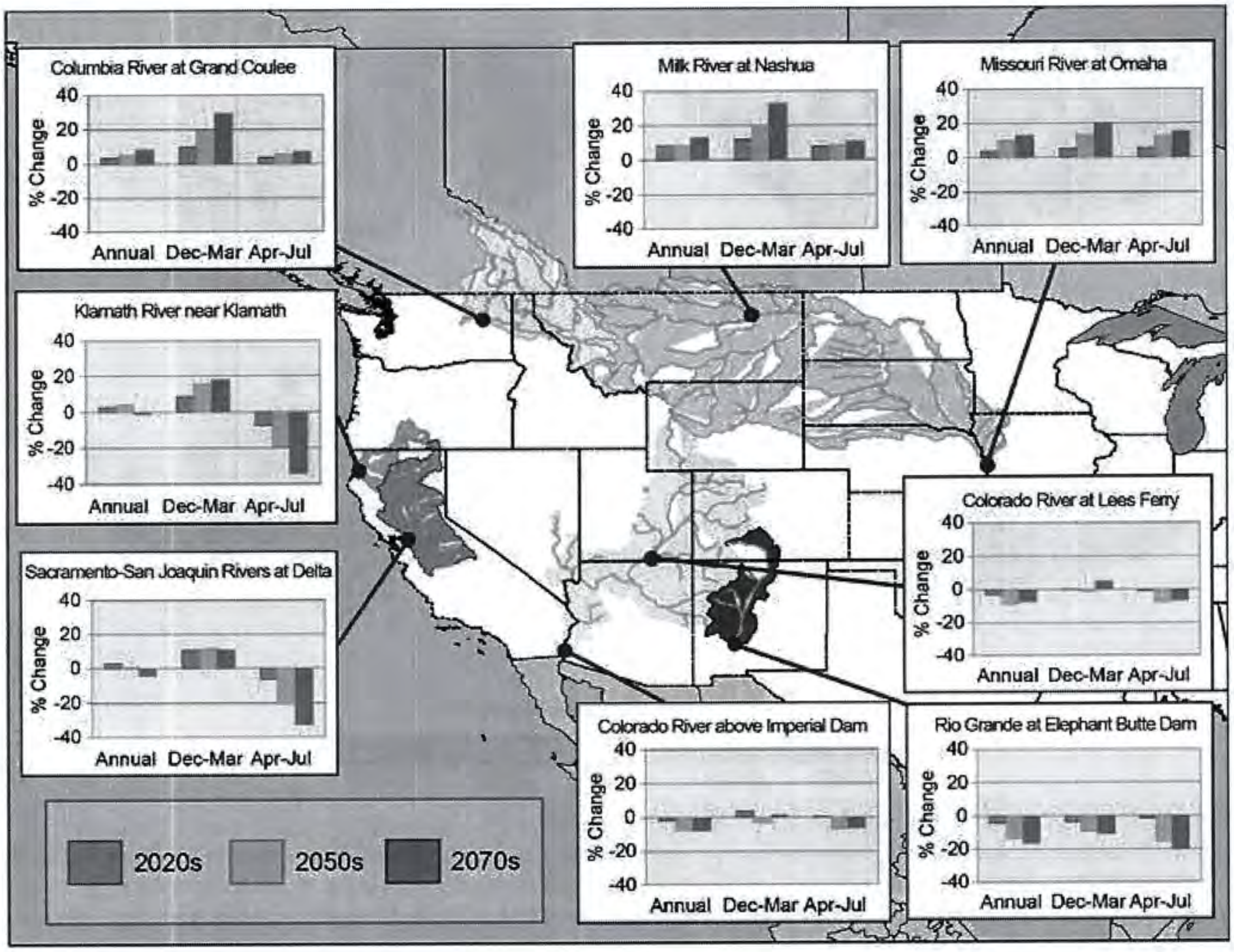


Figure 3.4. Annual and seasonal streamflow projections based on the B1 (with substantial emissions reductions), A1B (with gradual reductions from current emission trends beginning around mid-century), and A2 (with continuation of current rising emissions trends) CMIP3 scenarios for eight river basins in the western United States. The panels show percentage changes in average runoff, with projected increases above the zero line and decreases below. Projections are for annual, cool, and warm seasons, for three future decades (2020s, 2050s, and 2070s) relative to the 1990s. (Source: U.S. Department of the Interior – Bureau of Reclamation 2011;[41] Data provided by L. Brekke, S. Gangopadhyay, and T. Pruitt)

Columbia and the Missouri River basins) are projected to experience little change through the middle of this century, and increases by late this century.

Projected changes in runoff differ by season, with cool season runoff increasing over the west coast basins from California to Washington and over the north-central U.S. (for example, the San Joaquin, Sacramento, Klamath, Missouri, and Columbia River basins). Basins in the southwestern U.S. and southern Rockies are projected to see little change to slight decreases in the winter months.

Warm season runoff is projected to decrease substantially over a region spanning southern Oregon, the southwestern U.S., and southern Rockies (for example, the Klamath, Sacramento, San Joaquin, Rio Grande, and the Colorado River basins), and change little or increase slightly north of this region (for example, the Columbia and Missouri River basins).

In most of these western basins, these projected streamflow changes are outside the range of historical variability, especially by the 2050s and 2070s. The projected streamflow changes and associated uncertainties have water management implications (discussed below).

Key Message 2: Droughts Intensify

Short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast.

Annual runoff and related river-flow are projected to decline in the Southwest[42,43] and Southeast,[34] and to increase in the Northeast, Alaska, Northwest, and upper Midwest regions,[42,43,44,45] broadly mirroring projected precipitation patterns.[46] Observational studies[47] have shown that decadal fluctuations in average temperature (up to 1.5°F) and precipitation changes of 10% have occurred in most areas of the U.S. during the last century. Fluctuations in river-flow indicate that effects of temperature are dominated by fluctuations in precipitation. Nevertheless, as warming affects water cycle processes, the amount of runoff generated by a given amount of precipitation is generally expected to decline.[37]

Droughts occur on time scales ranging from season-to-season to multiple years and even multiple decades. There has been no universal trend in the overall extent of drought across the continental U.S. since 1900. However, in the Southwest, widespread drought in the past decade has reflected both precipitation deficits and higher temperatures[8] in ways that resemble projected changes.[48] Long-term (multi-seasonal) drought conditions are also projected to increase in parts of the Southeast and possibly in Hawai'i and the Pacific Islands (Ch. 23: Hawai'i and Pacific Islands). Except in the few areas where increases in summer precipitation compensate, summer droughts (Ch. 2: Our Changing Climate) are expected to intensify almost everywhere in the continental U.S.[49] due to longer periods of dry weather and more extreme heat,[33] leading to more moisture loss from plants and earlier soil moisture depletion in basins where snowmelt shifts to earlier in the year.[50,51] Basins watered by glacial melt in the Sierra Nevada, Glacier National Park, and Alaska may experience increased summer river-flow in the next few decades, until the amounts of glacial ice become too small to contribute to river-flow.[52,53]

Key Message 3: Increased Risk of Flooding in Many Parts of the U.S.

Flooding may intensify in many U.S. regions, even in areas where total precipitation is projected to decline.

There are various types of floods (see "Flood Factors and Flood Types"), some of which are projected to increase with continued climate change. Floods that are closely tied to heavy precipitation events, such as flash floods and urban floods, as well as coastal floods related to sea level rise and the resulting increase in storm surge height and inland impacts, are expected to increase. Other types of floods result from a more complex set of causes. For example, river floods are basin specific and dependent not only on precipitation but also on pre-existing soil moisture conditions, topography, and other factors, including important human-caused changes to watersheds and river courses across the United States.[54,55,56,57]

Significant changes in annual precipitation (Ch. 2: Our Changing Climate) and soil moisture (Figures 3.2 and 3.3), among other factors, are expected to affect annual flood magnitudes (Figure 3.5) in many regions.[58] River floods have been increasing in the Northeast and Midwest, and decreasing in the Southwest and Southeast.[56,57,58,59] These decreases are not surprising, as short duration very heavy precipitation events often occur during the summer and autumn when rivers are generally low. However, these very heavy precipitation events can and do lead to flash floods, often exacerbated in urban areas by the effect of impervious surfaces on runoff.

Heavy rainfall events are projected to increase, which is expected to increase the potential for flash flooding. Land cover, flow and water-supply management, soil moisture, and channel conditions are also important influences on flood generation[55] and must be considered in projections of future flood risks. Region-specific storm mechanisms and seasonality also affect flood peaks.[57] Because of this, and limited capacity to project future very heavy events with confidence, evaluations of the relative changes in various storm mechanisms may be useful.[57,60,61] Warming is likely to directly affect flooding in many mountain settings, as catchment areas receive increasingly more precipitation as rain rather than snow, or more rain falling on existing snowpack.[62] In some such settings, river flooding may increase as a result – even where precipitation and overall river flows decline (Ch. 2: Our Changing Climate).

Trends in Flood Magnitude

Figure 3.5. Trend magnitude (triangle size) and direction (green = increasing trend, brown = decreasing trend) of annual flood magnitude from the 1920s through 2008. Flooding in local areas can be affected by multiple factors, including land-use change, dams, and diversions of water for use. Most significant are increasing trends for floods in Midwest and Northeast, and a decreasing trend in the Southwest. (Figure source: Peterson et al. 2013[63]).

Key Message 4: Groundwater Availability

Climate change is expected to affect water demand, groundwater withdrawals, and aquifer recharge, reducing groundwater availability in some areas.

Groundwater is the only perennial source of fresh water in many regions and provides a buffer against climate extremes. As such, it is essential to water supplies, food security, and ecosystems. Though groundwater occurs in most areas of the U.S., the capacity of aquifers to store water varies depending on the geology of the region. (Figure 3.6b illustrates the importance of groundwater aquifers.) In large regions of the Southwest, Great Plains, Midwest, Florida, and some other coastal areas, groundwater is the primary water supply. Groundwater aquifers in these areas are susceptible to the combined stresses of climate and water-use changes. For example, during the 2006–2009 California drought, when the source of irrigation shifted from surface water to predominantly groundwater, groundwater storage in California's Central Valley declined by an amount roughly equivalent to the storage capacity of Lake Mead, the largest reservoir in the United States.[64]

Climate change impacts on groundwater storage are expected to vary from place to place and aquifer to aquifer. Although precise responses of groundwater storage and flow to climate change are not well understood nor readily generalizable, recent and ongoing studies[65,66,67,68] provide insights on various underlying mechanisms:

1) Precipitation is the key driver of aquifer recharge in water-limited environments (like arid regions), while evapotranspiration (ET) is the key driver in energy-limited environments (like swamps or marshlands).

2) Climate change impacts on aquifer recharge depend on several factors, including basin geology, frequency and intensity of high-rainfall periods that drive recharge, seasonal timing of recharge events, and strength of groundwater-surface water interaction.

3) Changes in recharge rates are amplified relative to changes in total precipitation, with greater amplification for drier areas.

With these insights in mind, it is clear that certain groundwater-dependent regions are projected to incur significant climate change related challenges. In some portions of the country, groundwater provides nearly 100% of the water supply (Figure 3.6b). Seasonal soil moisture changes are a key aquifer recharge driver and may provide an early indication of general aquifer recharge trends. Thus, the observed regional reductions in seasonal soil moisture for winter and spring (Figure 3.3) portend adverse recharge impacts for several U.S. regions, especially the Great Plains, Southwest, and Southeast.

Despite their critical national importance as water supply sources (see Figure 3.6), aquifers are not generally monitored

Principal U.S. Groundwater Aquifers and Use

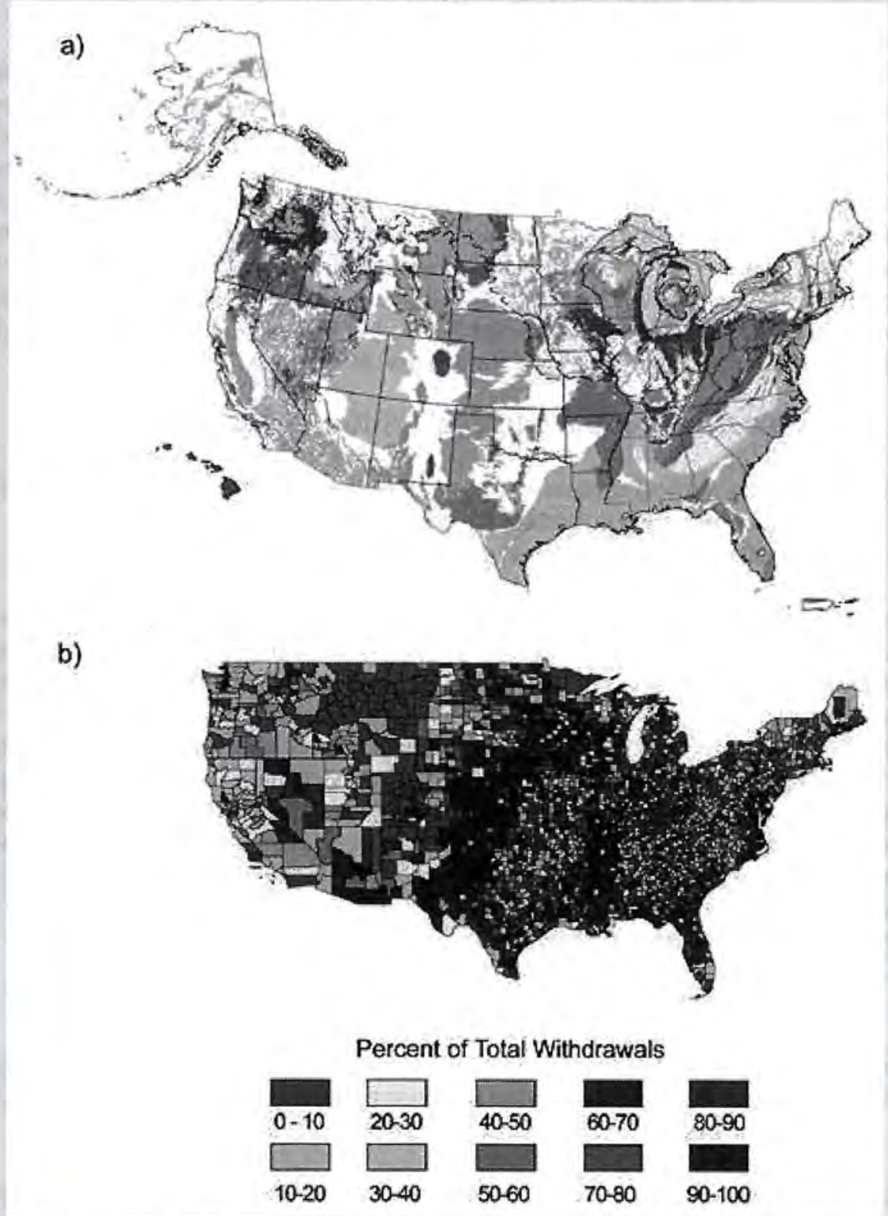


Figure 3.6. (**a**) Groundwater aquifers are found throughout the U.S., but they vary widely in terms of ability to store and recharge water. The colors on this map illustrate aquifer location and geology: blue colors indicate unconsolidated sand and gravel; yellow is semi-consolidated sand; green is sandstone; blue or purple is sandstone and carbonate-rock; browns are carbonate-rock; red is igneous and metamorphic rock; and white is other aquifer types. (Figure source: USGS). (**b**) Ratio of groundwater withdrawals to total water withdrawals from all surface and groundwater sources by county. The map illustrates that aquifers are the main (and often exclusive) water supply source for many U.S. regions, especially in the Great Plains, Misssissippi Valley, east central U.S., Great Lakes region, Florida, and other coastal areas. Groundwater aquifers in these regions are prone to impacts due to combined climate and water-use change. (Data from USGS 2005).

in ways that allow for clear identification of climatic influences on groundwater recharge, storage, flows, and discharge. Nearly all monitoring is focused in areas and aquifers where variations are dominated by groundwater pumping, which largely masks climatic influences,[69] highlighting the need for a national framework for groundwater monitoring.[70]

Generally, impacts of changing demands on groundwater systems, whether due directly to climate changes or indirectly through changes in land use or surface-water availability and management, are likely to have the most immediate effects on groundwater availability;[67,71] changes in recharge and storage may be more subtle and take longer to emerge. Groundwater models have only recently begun to include detailed representations of groundwater recharge and interactions with surface-water and land-surface processes,[50] with few projections of groundwater responses to climate change.[68,72] However, surface water declines have already resulted in larger groundwater withdrawals in some areas (for example, in the Central Valley of California and in the Southeast) and may be aggravated by climate change challenges.[73] In many mountainous areas of the U.S., groundwater recharge is disproportionately generated from snowmelt infiltration, suggesting that the loss of snowpack will affect recharge rates and patterns.[50,51,66,74] Models do not yet include dynamic representations of the groundwater reservoir and its connections to streams, the soil-vegetation system, and the atmosphere, limiting the understanding of the potential climate change impacts on groundwater and groundwater-reliant systems.[75]

As the risk of drought increases, groundwater can play a key role in enabling adaptation to climate variability and change. For example, groundwater can be augmented by surface water during times of high flow through aquifer recharge strategies, such as infiltration basins and injection wells. In addition, management strategies can be implemented that use surface water for irrigation and water supply during wet periods, and groundwater during drought, although these approaches face practical limitations within current management and institutional frameworks.[71,76]

Key Message 5: Risks to Coastal Aquifers and Wetlands

Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands.

With more than 50% of the nation's population concentrated near coasts (Chapter 25: Coasts),[77] coastal aquifers and wetlands are precious resources. These aquifers and wetlands, which are extremely important from a biological/biodiversity perspective (see Ch. 8: Ecosystems; Ch. 25: Coasts), may be particularly at risk due to the combined effects of inland droughts and floods, increased surface water impoundments and diversions, increased groundwater withdrawals, and accelerating sea level rise and greater storm surges.[78,79] Estuaries are particularly vulnerable to changes in freshwater inflow and sea level rise by changing salinity and habitat of these areas.

Several coastal areas, including the Delaware, Susquehanna, and Potomac River deltas on the Northeast seaboard, most of Florida, the Apalachicola and Mobile River deltas and bays, the Mississippi River delta in Louisiana, and the delta of the Sacramento-San Joaquin rivers in northern California, are particularly vulnerable due to the combined effects of climate change and other human-caused stresses. In response, some coastal communities are among the nation's most proactive in adaptation planning (Chapter 25: Coasts).

Key Message 6: Water Quality Risks to Lakes and Rivers

Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and other pollutant loads.

Water temperature has been increasing in some rivers.[80] The length of the season that lakes and reservoirs are thermally stratified (with separate density layers) is increasing with increased air and water temperatures.[81,82] In some cases, seasonal mixing may be eliminated in shallow lakes, decreasing dissolved oxygen and leading to excess concentrations of nutrients (nitrogen and phosphorous), heavy metals (such as mercury), and other toxins in lake waters.[81,82]

Lower and more persistent low flows under drought conditions as well as higher flows during floods can worsen water quality. Increasing precipitation intensity, along with the effects of wildfires and fertilizer use, are increasing sediment, nutrient, and contaminant loads in surface waters used by downstream water users[84] and ecosystems. Mineral weathering products, like calcium, magnesium, sodium, and silicon and nitrogen loads[85] have been increasing with higher streamflows.[86] Changing land cover, flood frequencies, and flood magnitudes are expected to increase mobilization of sediments in large river basins.[87]

Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease water quality in many ways. Here, middle school students in Colorado learn about water quality.

Changes in sediment transport are expected to vary regionally and by land-use type, with potentially large increases in some areas,[88] resulting in alterations to reservoir storage and river channels, affecting flooding, navigation, water supply, and dredging. Increased frequency and duration of droughts, and associated low water levels, increase nutrient concentrations and residence times in streams, potentially increasing the likelihood of harmful algal blooms and low oxygen conditions.[89] Concerns over such impacts and their potential link to climate change are rising for many U.S. regions including the Great Lakes,[90] Chesapeake Bay,[91] and the Gulf of Mexico.[85,86] Strategies aiming to reduce sediment, nutrient, and contaminant loads at the source remain the most effective management responses.[92]

Observed Changes in Lake Stratification and Ice Covered Area

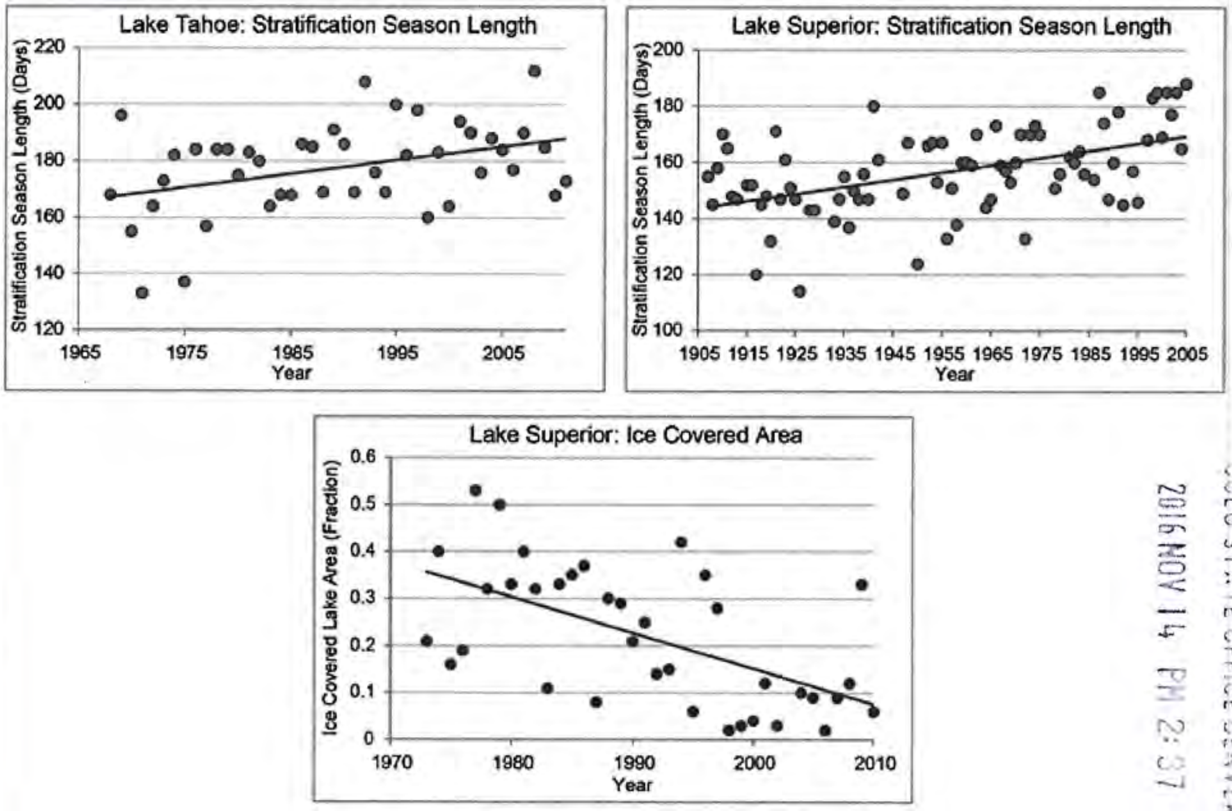


Figure 3.7. The length of the season in which differences in lake temperatures with depth cause stratification (separate density layers) is increasing in many lakes. In this case, measurements show stratification has been increasing in Lake Tahoe (top left) since the 1960s and in Lake Superior (top right) since the early 1900s in response to increasing air and surface water temperatures (see also Ch. 18: Midwest). In Lake Tahoe, because of its large size (relative to inflow) and resulting long water-residence times, other influences on stratification have been largely overwhelmed, and warming air and water temperatures have caused progressive declines in near-surface density, leading to longer stratification seasons (by an average of 20 days), decreasing the opportunities for deep lake mixing, reducing oxygen levels, and causing impacts to many species and numerous aspects of aquatic ecosystems.[83] Similar effects are observed in Lake Superior,[16] where the stratification season is lengthening (top right) and annual ice-covered area is declining (bottom); both observed changes are consistent with increasing air and water temperatures.

Relationship between Historical and Projected Water Cycle Changes

Natural climate variations occur on essentially all time scales from days to millennia, and the water cycle varies in much the same way. Observations of changes in the water cycle over time include responses to natural hydroclimatic variability as well as other, more local, human influences (like dam building or land-use changes), or combinations of these influences with human-caused climate change. Some recent studies have attributed specific observed changes in the water cycle to human-induced climate change (for example, Barnett et al. 2008[10]). For many other water cycle variables and impacts, the observed and projected responses are consistent with those expected by human-induced climate change and other human influences. Research aiming to formally attribute these responses to their underlying causes is ongoing.

FLOOD FACTORS AND FLOOD TYPES

A flood is defined as any high flow, overflow, or inundation by water that causes or threatens damage.[93] Floods are caused or amplified by both weather- and human-related factors. Major weather factors include heavy or prolonged precipitation, snowmelt, thunderstorms, storm surges from hurricanes, and ice or debris jams. Human factors include structural failures of dams and levees, inadequate drainage, and land cover alterations (such as pavement or deforestation) that reduce the capacity of the land surface to absorb water. Increasingly, humanity is also adding to weather-related factors, as human-induced warming increases heavy downpours, causes more extensive storm surges due to sea level rise, and leads to more rapid spring snowmelt.

Worldwide, from 1980 to 2009, floods caused more than 500,000 deaths and affected more than 2.8 billion people.[94] In the U.S., floods caused 4,586 deaths from 1959 to 2005[95] while property and crop damage averaged nearly $8 billion per year (in 2011 dollars) over 1981 through 2011.[93] The risks from future floods are significant, given expanded development in coastal areas and floodplains, unabated urbanization, land-use changes, and human-induced climate change.[94]

Major flood types include flash, urban, riverine, and coastal flooding:

Flash floods occur in small and steep watersheds and waterways and can be caused by short-duration intense precipitation, dam or levee failure, or collapse of debris and ice jams. Snow cover and frozen ground conditions can exacerbate flash flooding during winter and early spring by increasing the fraction of precipitation that runs off. Flash floods develop within minutes or hours of the causative event, and can result in severe damage and loss of life due to high water velocity, heavy debris load, and limited warning. Most flood-related deaths in the U.S. are associated with flash floods.

Flash Flooding: Cave Creek, Arizona (Photo credit: Tom McGuire).

Urban flooding can be caused by short-duration very heavy precipitation. Urbanization creates large areas of impervious surfaces (such as roads, pavement, parking lots, and buildings) and increases immediate runoff. Stormwater drainage removes excess surface water as quickly as possible, but heavy downpours can exceed the capacity of drains and cause urban flooding.

Flash floods and urban flooding are directly linked to heavy precipitation and are expected to increase as a result of projected increases in heavy precipitation events. In mountainous watersheds, such increases may be partially offset in winter and spring due to projected snowpack reduction.

Riverine Flooding: In many regions, infrastructure is currently vulnerable to flooding, as demonstrated in these photos. Left: The Fort Calhoun Nuclear Power Plant in eastern Nebraska was surrounded by a Missouri River flood on June 8, 2011, that also affected Louisiana, Mississippi, Missouri, Illinois, Kentucky, Tennessee, and Arkansas (photo credit: Larry Geiger). Right: The R.M. Clayton sewage treatment plant in Atlanta, Georgia, September 23, 2009, was engulfed by floodwaters forcing it to shut down and resulting in the discharge of raw sewage into the Chattahoochee River (photo credit: Reuters/David Tulis). Flooding also disrupts road and rail transportation, and inland navigation.

Riverine flooding occurs when surface water drains from a watershed into a stream or a river exceeds channel capacity, overflows the

Continued

FLOOD FACTORS AND FLOOD TYPES (CONTINUED)

banks, and inundates adjacent low lying areas. Riverine flooding is commonly associated with large watersheds and rivers, while flash and urban flooding occurs in smaller natural or urban watersheds. Because heavy precipitation is often localized, riverine flooding typically results from multiple heavy precipitation events over periods of several days, weeks, or even months. In large basins, existing soil moisture conditions and evapotranspiration rates also influence the onset and severity of flooding, as runoff increases with wetter soil and/or lower evapotranspiration conditions. Snow cover and frozen ground conditions can also exacerbate riverine flooding during winter and spring by increasing runoff associated with rain-on-snow events and by snowmelt, although these effects may diminish in the long term as snow accumulation decreases due to warming. Since riverine flooding depends on precipitation as well as many other factors, projections about changes in frequency or intensity are more uncertain than with flash and urban flooding.

Coastal flooding is predominantly caused by storm surges that accompany hurricanes and other storms. Low storm pressure creates strong winds that create and push large sea water domes, often many miles across, toward the shore. The approaching domes can raise the water surface above normal tide levels (storm surge) by more than 25 feet, depending on various storm and shoreline factors. Inundation, battering waves, and floating debris associated with storm surge can cause deaths, widespread infrastructure damage (to buildings, roads, bridges, marinas, piers, boardwalks, and sea walls), and severe beach erosion. Storm-related rainfall can also cause inland flooding (flash, urban, or riverine) if, after landfall, the storm moves slowly or stalls over an area. Inland flooding can occur close to the shore or hundreds of miles away and is responsible for more than half of the deaths associated with tropical storms.[93] Climate change affects coastal flooding through sea level rise and storm surge, increases in heavy rainfall during hurricanes and other storms, and related increases in flooding in coastal rivers.

Hurricane Sandy coastal flooding in Mantoloking, N.J. (Photo credit: New Jersey National Guard/Scott Anema).

In some locations, early warning systems have helped reduce deaths, although property damage remains considerable (Ch. 28: Adaptation). Further improvements can be made by more effective communication strategies and better land-use planning.[94]

Climate Change Impacts on Water Resource Uses and Management

People use water for many different purposes and benefits. Our water use falls into five main categories: 1) municipal use, which includes domestic water for drinking and bathing; 2) agricultural use, which includes irrigation and cattle operations; 3) industrial use, which includes electricity production from coal- or gas-fired power plants that require water to keep the machinery cool; 4) providing ecosystem benefits, such as supporting the water needs of plants and animals we depend on; and 5) recreational uses, such as boating and fishing.

Water is supplied for these many uses from two main sources:

- freshwater withdrawals (from streams, rivers, lakes, and aquifers), which supply water for municipal, industrial, agricultural, and recirculating thermoelectric plant cooling water supply;
- instream surface water flows, which support hydropower production, once-through thermoelectric plant cooling, navigation, recreation, and healthy ecosystems.

Key Message 7: Changes to Water Demand and Use

Climate change affects water demand and the ways water is used within and across regions and economic sectors. The Southwest, Great Plains, and Southeast are particularly vulnerable to changes in water supply and demand.

Climate change, acting concurrently with demographic, land-use, energy generation and use, and socioeconomic changes, is challenging existing water management practices by affecting water availability and demand and by exacerbating competition among uses and users (see Ch. 4: Energy; Ch. 6: Agriculture; Ch. 10: Energy, Water, and Land; Ch. 12: Indigenous Peoples; and Ch. 13: Land Use & Land Cover Change). In some regions, these current and expected impacts are hastening efficiency improvements in water withdrawal and use, the deployment of more proactive water management and adaptation approaches, and the reassessment of the water infrastructure and institutional responses.[1]

Water Withdrawals

Total freshwater withdrawals (including water that is withdrawn and consumed as well as water that returns to the original source) and consumptive uses have leveled off nationally since 1980 at 350 billion gallons of withdrawn water and 100 billion gallons of consumptive water per day, despite the addition of 68 million people from 1980 to 2005 (Figure 3.8).[96] Irrigation and all electric power plant cooling withdrawals account for approximately 77% of total withdrawals, municipal and industrial for 20%, and livestock and aquaculture for 3%. Most thermoelectric withdrawals are returned back to rivers after cooling, while most irrigation withdrawals are consumed by the processes of evapotranspiration and plant growth. Thus, consumptive water use is dominated by irrigation (81%) followed distantly by municipal and industrial (8%) and the remaining water uses (5%). See Figure 3.9.

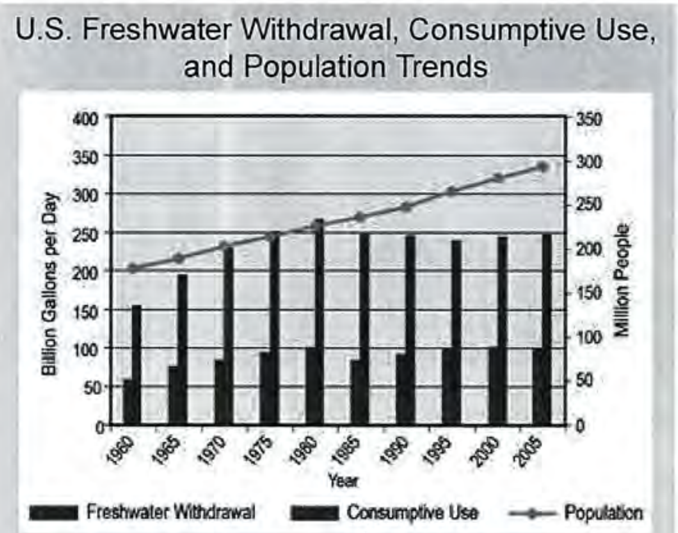


Figure 3.8. Trends in total freshwater withdrawal (equal to the sum of consumptive use and return flows to rivers) and population in the contiguous United States. This graph illustrates the remarkable change in the relationship between water use and population growth since about 1980. Reductions in per capita water withdrawals are directly related to increases in irrigation efficiency for agriculture, more efficient cooling processes in electrical generation, and, in many areas, price signals, more efficient indoor plumbing fixtures and appliances, and reductions in exterior landscape watering, in addition to shifts in land-use patterns in some areas.[97] Efficiency improvements have offset the demands of a growing population and have resulted in more flexibility in meeting water demand. In some cases these improvements have also reduced the flexibility to scale back water use in times of drought because some inefficiencies have already been removed from the system. With drought stress projected to increase in many U.S. regions, drought vulnerability is also expected to rise.[1]

Water sector withdrawals and uses vary significantly by region. There is a notable east-west water use pattern, with the largest regional withdrawals occurring in western states (where the climate is drier) for agricultural irrigation (Figure 3.10a,d). In the east, water withdrawals mainly serve municipal, industrial, and thermoelectric uses (Figure 3.10a,b,c). Irrigation is also dominant along the Mississippi Valley, in Florida, and in southeastern Texas. Groundwater withdrawals are especially intense in parts of the Southwest, Southeast, Northwest, and

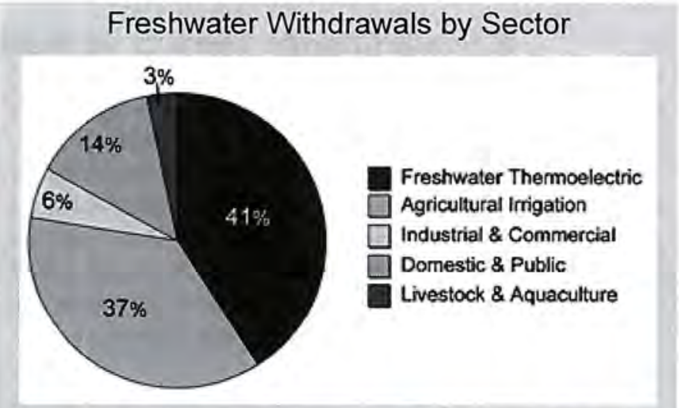
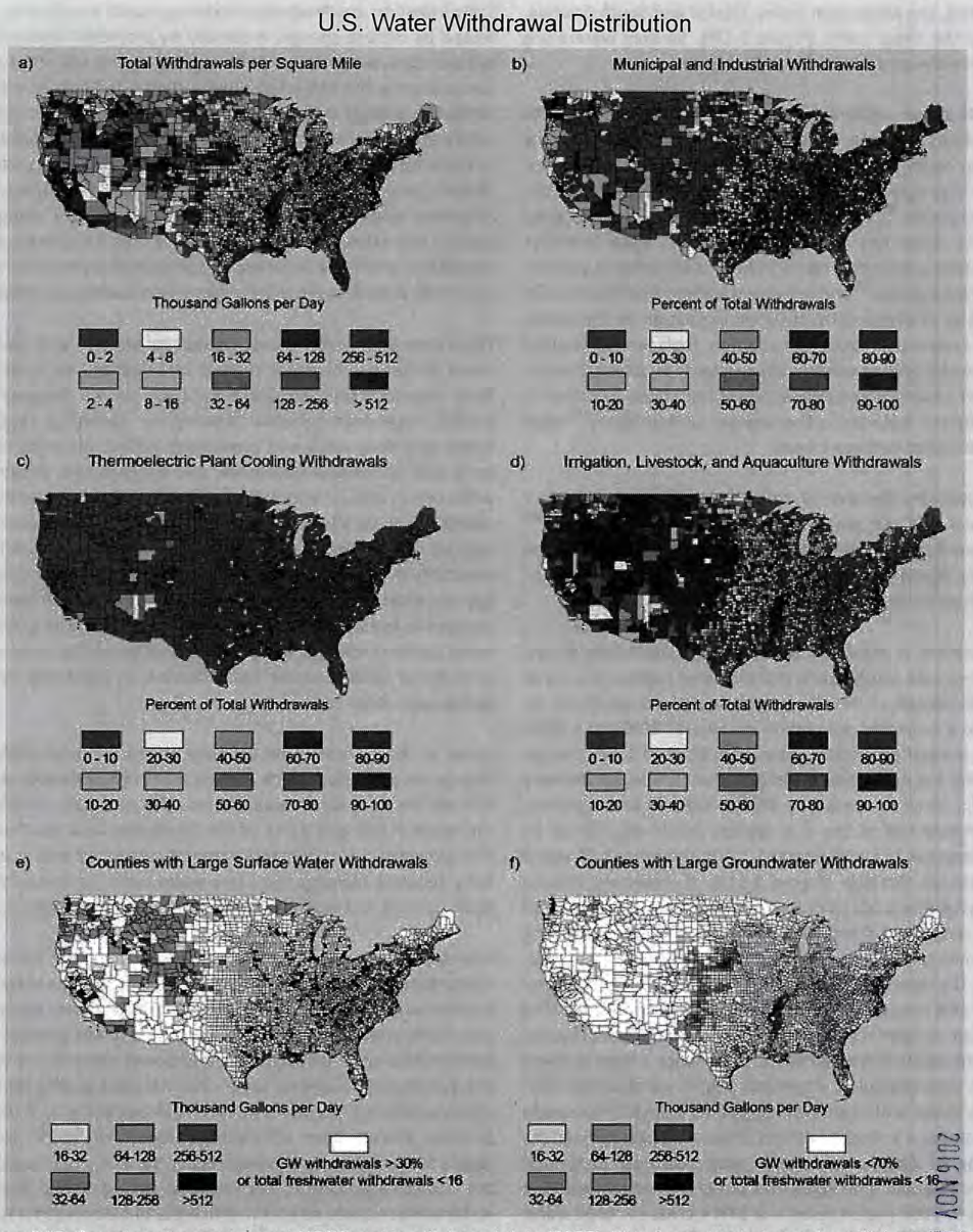


Figure 3.9. Total water withdrawals (groundwater and surface water) in the U.S. are dominated by agriculture and energy production, though the primary use of water for thermoelectric production is for cooling, where water is often returned to lakes and rivers after use (return flows). (Data from Kenny et al. 2009[96])



U.S. Water Withdrawal Distribution

Figure 3.10. Based on the most recent USGS water withdrawal data (2005). This figure illustrates water withdrawals at the U.S. county level: (a) total withdrawals (surface and groundwater) in thousands of gallons per day per square mile; (b) municipal and industrial (including golf course irrigation) withdrawals as percent of total; (c) irrigation, livestock, and aquaculture withdrawals as percent of total; (d) thermoelectric plant cooling withdrawals as percent of total; (e) counties with large surface water withdrawals; and (f) counties with large groundwater withdrawals. The largest withdrawals occur in the drier western states for crop irrigation. In the east, water withdrawals mainly serve municipal, industrial, and thermoelectric uses. Groundwater withdrawals are intense in parts of the Southwest and Northwest, the Great Plains, Mississippi Valley, Florida and South Georgia, and near the Great Lakes (Figure source: Georgia Water Resources Institute, Georgia Institute of Technology; Data from Kenny et al. 2009;[96] USGS 2013[98]).

Great Plains, the Mississippi Valley, Florida and South Georgia, and near the Great Lakes (Figure 3.10f). Surface waters are most intensely used in all other U.S. regions.

Per capita water withdrawal and use are decreasing due to many factors.[99] These include demand management, new plumbing codes, water-efficient appliances, efficiency improvement programs, and pricing strategies, especially in the municipal sector.[100] Other factors contributing to decreasing per capita water use include changes from water-intensive manufacturing and other heavy industrial activities to service-oriented businesses,[101] and enhanced water-use efficiencies in response to environmental pollution legislation (in the industrial and commercial sector). In addition, replacement of older once-through-cooling electric power plants by plants that recycle their cooling water, and switching from flood irrigation to more efficient methods in the western United States[102] have also contributed to these trends.

Notwithstanding the overall national trends, regional water withdrawal and use are strongly correlated with climate;[103] hotter and drier regions tend to have higher per capita usage, and water demand is affected by both temperature and precipitation on a seasonal basis (see also Ch. 28: Adaptation).

Water demand is projected to increase as population grows, and will increase substantially more in some regions as a result of climate change. In the absence of climate change but in response to a projected population increase of 80% and a 245% increase in total personal income from 2005 to 2060, simulations under the A1B scenario indicate that total water demand in the U.S. would increase by 3%.[99] Under these conditions, approximately half of the U.S. regions would experience an overall decrease in water demand, while the other half would experience an increase (Figure 3.11a). If, however, climate change projections based on the A1B emissions scenario (with gradual reductions from current emission trends beginning around mid-century) and three climate models are also factored in, the total water demand is projected to rise by an average of 26% over the same period (Figure 3.11b).[99] Under the population increase scenario that also includes climate change, 90% of the country is projected to experience a total demand increase, with decreases projected only in parts of the Midwest, Northeast and Southeast. Compared to an 8% increase in demand under a scenario without climate change, projections under the A2 emissions scenario (which assumes continued increases in global emissions) and three climate models over the 2005 to 2060 period result in a 34% increase in total water demand. By 2090, total water demand is projected to increase by 42% over 2005 levels under the A1B scenario and 82% under the higher A2 emissions scenario.

Crop irrigation and landscape watering needs are directly affected by climate change, especially by projected changes in temperature, potential evapotranspiration, and soil moisture. Consequently, the projected climate change impacts on water demand are larger in the western states, where irrigation dominates total water withdrawals (see Figure 3.10). Uncertainties in the projections of these climate variables also affect water demand projections.[99] However, it is clear that the impacts of projected population, socioeconomic, and climate changes amplify the effects on water demand in the Southwest and Southeast, where the observed and projected drying water cycle trends already make these regions particularly vulnerable.

This vulnerability will be exacerbated by physical and operational limitations of water storage and distribution systems. River reservoirs and associated dams are usually designed to handle larger-than-historical streamflow variability ranges. Some operating rules and procedures reflect historical seasonal and interannual streamflow and water release patterns, while others include information about current and near-term conditions, such as snowpack depth and expected snowmelt volume. Climate change threatens to alter both the streamflow variability that these structures must accommodate and their opportunities to recover after doing so (due to permanent changes in average streamflow). Thus, as streamflow and demand patterns change, historically based operating rules and procedures could become less effective in balancing water supply with other uses.[104]

Some of the highest water demand increases under climate change are projected in U.S. regions where groundwater aquifers are the main water supply source (Figure 3.11b), including the Great Plains and parts of the Southwest and Southeast. The projected water demand increases combined with potentially declining recharge rates (see water cycle section) further challenge the sustainability of the aquifers in these regions.

Power plant cooling is a critical national water use, because nearly 90% of the U.S. electrical energy is produced by thermoelectric power plants.[105] Freshwater withdrawals per kilowatt hour have been falling in recent years due to the gradual replacement of once-through cooling of power plant towers with plants that recycle cooling water. Thermal plant cooling is principally supported by surface water withdrawals (Figure 3.10e,f) and has already been affected by climate change in areas where temperatures are increasing and surface water supplies are diminishing, such as the southern United States. Higher water temperatures affect the efficiency of electric generation and cooling processes. It also limits the ability of utilities to discharge heated water to streams from once-through cooled power systems due to regulatory requirements and concerns about how the release of warmer water into rivers and streams affects ecosystems and biodiversity (see Ch. 4: Energy).[106]

Projected Changes in Water Withdrawals

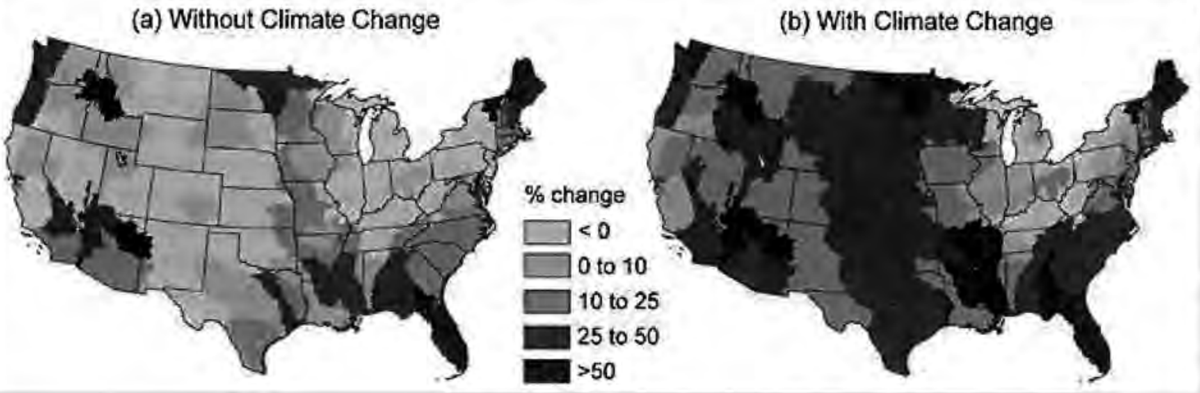


Figure 3.11. The effects of climate change, primarily associated with increasing temperatures and potential evapotranspiration, are projected to significantly increase water demand across most of the United States. Maps show percent change from 2005 to 2060 in projected demand for water assuming (a) change in population and socioeconomic conditions based on the underlying A1B emissions scenario, but with no change in climate, and (b) combined changes in population, socioeconomic conditions, and climate according to the A1B emissions scenario (gradual reductions from current emission trends beginning around mid-century). (Figure source: Brown et al. 2013[99]).

Instream Water Uses

Hydropower contributes 7% of electricity generation nationwide, but provides up to 70% in the Northwest and 20% in California, Alaska, and the Northeast.[107] Climate change is expected to affect hydropower directly through changes in runoff (average, extremes, and seasonality), and indirectly through increased competition with other water uses. Based on runoff projections, hydropower is expected to decline in the southern U.S. (especially the Southwest) and increase in the Northeast and Midwest (though actual gains or losses will depend on facility size and changes in runoff volume and timing). Where non-power water demands are expected to increase (as in the southern U.S.), hydropower generation, dependable capacity, and ancillary services are likely to decrease. Many hydropower facilities nationwide, especially in the Southeast, Southwest, and the Great Plains, are expected to face water availability constraints.[108] While some hydropower facilities may face water-related limitations, these could be offset to some degree by the use of more efficient turbines as well as innovative new hydropower technologies.

Inland navigation, most notably in the Great Lakes and the Missouri, Mississippi, and Ohio River systems, is particularly important for agricultural commodities (transported from the Midwest to the Gulf Coast and on to global food markets), coal, and iron ore.[1,109] Navigation is affected by ice cover and by floods and droughts. Seasonal ice cover on the Great Lakes has been decreasing[16] which may allow increased shipping.[110] However, lake level declines are also possible in the long term, decreasing vessel draft and cargo capacity. Future lake levels may also depend on non-climate factors and are uncertain both in direction and magnitude (see Ch. 2: Our Changing Climate; Ch. 5: Transportation; and Ch. 18: Midwest). Similarly, although the river ice cover period has been decreasing[53] (extending the inland navigation season), seasonal ice cover changes[111,112] could impede lock operations.[112] Intensified floods are likely to hinder shipping by causing waterway closures and damaging or destroying ports and locks. Droughts have already been shown to decrease reliability of flows or channel depth, adversely impacting navigation (Ch. 5: Transportation). Both floods and droughts can disrupt rail and road traffic and increase shipping costs[113] and result in commodity price volatility (Ch. 19: Great Plains).

Recreational activities associated with water resources, including boating, fishing, swimming, skiing, camping, and wildlife watching, are strong regional and national economic drivers.[114] Recreation is sensitive to weather and climate,[115] and climate change impacts to recreation can be difficult to project.[116] Rising temperatures affect extent of snowcover and mountain snowpack, with impacts on skiing[117] and snowmobiling.[118] As the climate warms, changes in precipitation and runoff are expected to result in both beneficial (in some regions) and adverse impacts[115] to water sports, with potential for considerable economic dislocation and job losses.[118]

Changing climate conditions are projected to affect water and wastewater treatment and disposal in ways that depend on system-specific and interacting attributes. For example, elevated stream temperatures, combined with lower flows, may require wastewater facilities to increase treatment to meet stream water quality standards.[119] More intense precipitation and floods, combined with escalating urbanization and associated increasing impermeable surfaces, may amplify the likelihood of contaminated overland flow or combined sewer overflows.[120] Moderate precipitation increases, however, could result in increased stream flows, improving capacity to dilute contaminants in some regions. Sea level rise and more frequent coastal flooding could damage wastewater utility infrastructure and reduce treatment efficiency (Ch. 25: Coasts).[121]

Changes in streamflow temperature and flow regimes can affect aquatic ecosystem structure and function (see Ch. 8: Ecosystems). Water temperature directly regulates the physiology, metabolism, and energy of individual aquatic organisms, as well as entire ecosystems. Streamflow quantity influences the extent of available aquatic habitats, and streamflow variability regulates species abundance and persistence. Flow also influences water temperature, sediment, and nutrient concentrations.[122] If the rate of climate change[123] outpaces plant and animal species' ability to adjust to temperature change, additional biodiversity loss may occur. Furthermore, climate change induced water cycle alterations may exacerbate existing ecosystem vulnerability, especially in the western United States[124] where droughts and water shortages are likely to increase. But areas projected to receive additional precipitation, such as the northern Great Plains, may benefit. Lastly, hydrologic alterations due to human interventions have without doubt impaired riverine ecosystems in most U.S. regions and globally.[125] The projected escalation of water withdrawals and uses (see Figure 3.11) threatens to deepen and widen ecosystem impairment, especially in southern states where climate change induced water cycle alterations are pointing toward drier conditions (see Ch. 8: Ecosystems). In these regions, balancing socioeconomic and environmental objectives will most likely require more deliberate management and institutional responses.

Major Water Resource Vulnerabilities and Challenges

Many U.S. regions are expected to face increased drought and flood vulnerabilities and exacerbated water management challenges. This section highlights regions where such issues are expected to be particularly intense.

Key Message 8: Drought is Affecting Water Supplies

Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. These trends are expected to continue, increasing the likelihood of water shortages for many uses.

Many southwestern and western watersheds, including the Colorado, Rio Grande,[38,43,126] and Sacramento-San Joaquin,[127,128] have recently experienced drier conditions. Even larger runoff reductions (about 10% to 20%) are projected over some of these watersheds in the next 50 years.[48,129] Increasing evaporative losses, declining runoff and groundwater recharge, and changing groundwater pumpage are expected to affect surface and groundwater supplies[65,66,67,71] and increase the risk of water shortages for many water uses. Changes in streamflow timing will exacerbate a growing mismatch between supply and demand (because peak flows are occurring earlier in the spring, while demand is highest in mid-summer) and will present challenges for the management of reservoirs, aquifers, and other water infrastructure.[130] Rising stream temperatures and longer low flow periods may make electric power plant cooling water withdrawals unreliable, and may affect aquatic and riparian ecosystems by degrading habitats and favoring invasive, non-native species.[131]

Key Message 9: Flood Effects on People and Communities

Increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the U.S.

Flooding affects critical water, wastewater, power, transportation, and communications infrastructure in ways that are difficult to foresee and can result in interconnected and cascading failures (see "Flood Factors and Flood Types"). Very heavy precipitation events have intensified in recent decades in most U.S. regions, and this trend is projected to continue (Ch. 2: Our Changing Climate). Increasing heavy precipitation is an important contributing factor, but flood magnitude changes also depend on specific watershed conditions (including soil moisture, impervious area, and other human-caused alterations).

Projected changes in flood frequency based on climate projections and hydrologic models have recently begun to emerge (for example, Das et al. 2012;[60] Brekke et al. 2009;[132] Raff et al. 2009;[133] Shaw and Riha 2011;[134] Walker et al. 2011[135]), and suggest that flood frequency and severity increases may occur in the Northeast and Midwest (Ch. 16: Northeast; Ch. 18: Midwest). Flooding and sea water intrusion from sea level rise and increasing storm surge threaten New York, Boston, Philadelphia, Virginia Beach, Wilmington, Charleston, Miami, Tampa, Naples, Mobile, Houston, New Orleans, and many other cities on U.S. coasts (Chapter 25: Coasts).

The devastating toll of large floods (human life, property, environment, and infrastructure) suggests that proactive management measures could minimize changing future flood risks and consequences (Ch. 28: Adaptation). In coastal areas, sea level rise may act in parallel with inland climate changes to intensify water-use impacts and challenges (Ch. 12: Indigenous Peoples; Ch. 17: Southeast).[136] Increasing flooding risk, both coastal and inland, could also exacerbate human health risks associated with failure of critical infrastructure,[137,138] and an increase in both waterborne diseases (Ch. 9: Human Health)[139] and airborne diseases.[140]

Changes in land use, land cover, development, and population distribution can all affect flood frequency and intensity. The nature and extent of these projected changes results in increased uncertainty and decreased accuracy of flood forecasting in both the short term[133] and long term.[141] This lack of certainty could hinder effective preparedness (such as evacuation planning) and the effectiveness of structural and non-structural flood risk reduction measures. However, many climate change projections are robust (Ch. 2: Our Changing Climate), and the long lead time needed for the planning, design, and construction of critical infrastructure that provides resilience to floods means that consideration of long-term changes is needed.

Effective climate change adaptation planning requires an integrated approach[45,118,142] that addresses public health and safety issues (Ch. 28: Adaptation).[143] Though numerous flood risk reduction measures are possible, including levees, land-use zoning, flood insurance, and restoration of natural floodplain retention capacity,[144] economic and institutional conditions may constrain implementation. The effective use of these measures would require significant investment in many cases,[145] as well as updating policies and methods to account for climate change[42,146] in the planning, design, operation, and maintenance of flood risk reduction infrastructure.[132,147]

Adaptation and Institutional Responses

Key Message 10: Water Resources Management

In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed within existing practices.

Water managers and planners strive to balance water supply and demand across all water uses and users. The management process involves complex tradeoffs among water-use benefits, consequences, and risks. By altering water availability and demand, climate change is likely to present additional management challenges. One example is in the Sacramento-San Joaquin River Delta, where flooding, sea water intrusion, and changing needs for environmental, municipal, and agricultural water uses have created significant management challenges. This California Bay-Delta experience suggests that managing risks and sharing benefits requires re-assessment of very complex ecosystems, infrastructure systems, water rights, stakeholder preferences, and reservoir operation strategies – as well as significant investments. All of these considerations are subject to large uncertainties.[54,148] To some extent, all U.S. regions are susceptible, but the Southeast and Southwest are highly vulnerable because climate change is projected to reduce water availability, increase demand, and exacerbate shortages (see "Water Management").

Recent assessments illustrate water management challenges facing California,[127,129,149,150] the Southwest,[130,151] Southeast (Ch. 17: Southeast),[136,152] Northwest,[153] Great Plains,[154] and Great Lakes.[155] A number of these assessments demonstrate that while expanding supplies and storage may still be possible in some regions, effective climate adaptation strategies can benefit from innovative management strategies. These strategies can include domestic water conservation programs that use pricing incentives to curb use; more flexible, risk-based, better-informed, and adaptive operating rules for reservoirs; the integrated use of combined surface and groundwater resources; and better monitoring and assessment of statewide water use.[129,149,156,157] Water management and planning would benefit from better coordination among public sectors at the national, state, and local levels (including regional partnerships and agreements), and the private sector, with participation of all relevant stakeholders in well-informed, fair, and equitable decision-making processes. Better coordination among hydrologists and atmospheric scientists, and among these scientists and the professional water management community is also needed to facilitate more effective translation of knowledge from science to practice (Ch. 26: Decision Support; Ch. 28: Adaptation).[158]

WATER CHALLENGES IN A SOUTHEAST RIVER BASIN

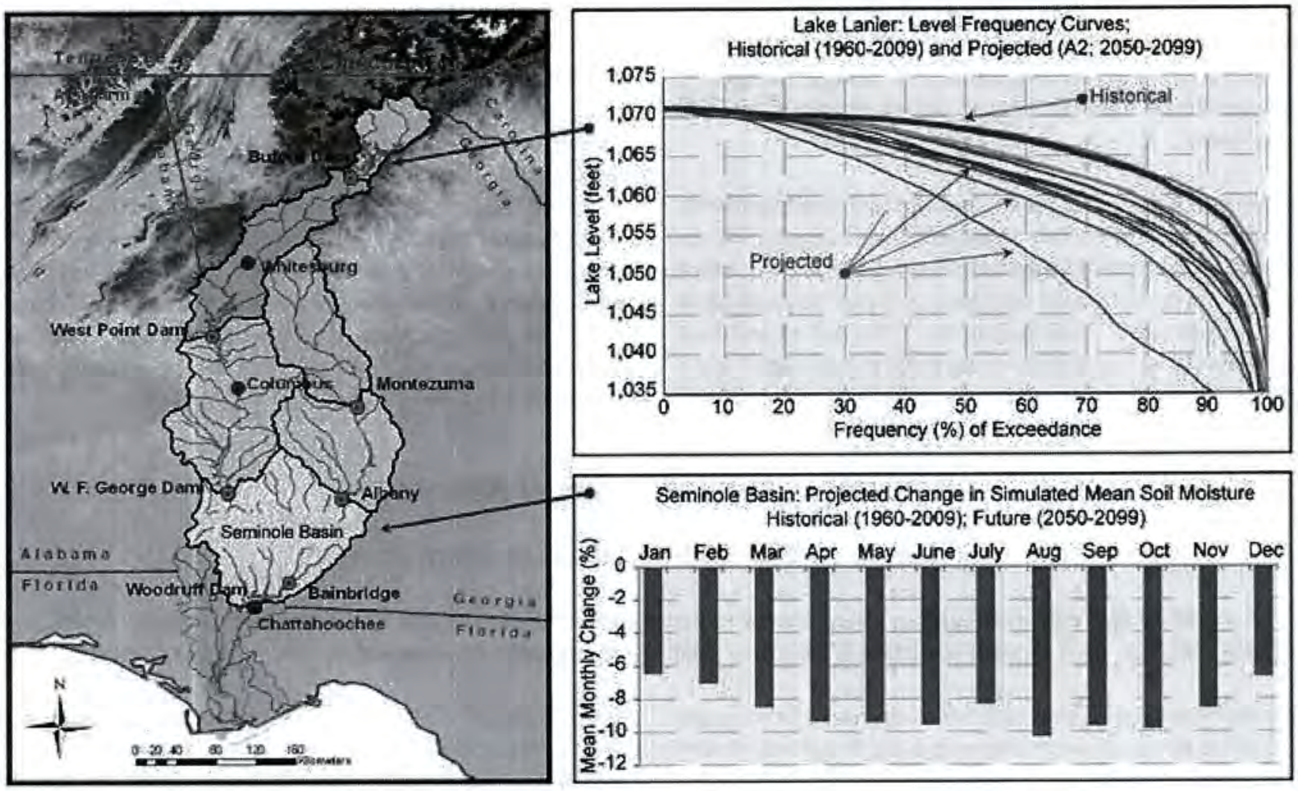


Figure 3.12. The Apalachicola-Chattahoochee-Flint (ACF) River Basin supports many water uses and users, including municipal, industrial, and agricultural water supply; flood management; hydroelectric and thermoelectric energy generation; recreation; navigation; fisheries; and a rich diversity of environmental and ecological resources. In recent decades, water demands have risen rapidly in the Upper Chattahoochee River (due to urban growth) and Lower Chattahoochee and Flint Rivers (due to expansion of irrigated agriculture). At the same time, basin precipitation, soil moisture, and runoff are declining, creating challenging water sharing tradeoffs for the basin stakeholders.[159] The historical water demand and supply trends are expected to continue in the coming decades. Climate assessments for 50 historical (1960-2009) and future years (2050-2099) based on a scenario of continued increases in emissions (A2) for the Seminole and all other ACF sub-basins[152] show that soil moisture is projected to continue to decline in all months, especially during the crop growing season from April to October (bottom right). Mean monthly runoff decreases (up to 20%, not shown) are also projected throughout the year and especially during the wet season from November to May. The projected soil moisture and runoff shifts are even more significant in the extreme values of the respective distributions. In addition to reduced supplies, these projections imply higher water demands in the agricultural and other sectors, exacerbating management challenges. These challenges are reflected in the projected response of Lake Lanier, the main ACF regulation project, the levels of which are projected (for 2050-2099) to be lower, by as much as 15 feet, than its historical (1960-2009) levels, particularly during droughts (top right). Recognizing these critical management challenges, the ACF stakeholders are earnestly working to develop a sustainable and equitable management plan that balances economic, ecological, and social values.[160] (Figure source: Georgia Water Resources Institute, Georgia Institute of Technology.[152]).

Key Message 11: Adaptation Opportunities and Challenges

Increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts. Many institutional, scientific, economic, and political barriers present challenges to implementing adaptive strategies.

Climate adaptation involves both addressing the risks and leveraging the opportunities that may arise as a result of the climate impacts on the water cycle and water resources. Efforts to increase resiliency and enhance adaptive capacity may create opportunities for a wide-ranging public discussion of water demands, improved collaboration around water use, increased public support for scientific and economic information, and the deployment of new technologies supporting adaptation. In addition, adaptation can promote the achievement of multiple water resource objectives through improved infrastructure planning, integrated regulation, and planning and management approaches at regional, watershed, or ecosystem scales. Pursuing these opportunities may require assessing how current institutional approaches support adaptation in light of the anticipated impacts of climate change.[161]

Climate change will stress the nation's aging water infrastructure to varying degrees by location and over time. Much of the country's current drainage infrastructure is already overwhelmed during heavy precipitation and high runoff events, an impact that is projected to be exacerbated as a result of climate change, land-use change, and other factors. Large percentage increases in combined sewage overflow volumes, associated with increased intensity of precipitation events, have been projected for selected watersheds by the end of this century in the absence of adaptive measures.[106,162] Infrastructure planning, especially for the long planning and operation horizons often associated with water resources infrastructure, can be improved by incorporating climate change as a factor in new design standards and in asset management and rehabilitation of critical and aging facilities, emphasizing flexibility, redundancy, and resiliency.[106,132,163]

Adaptation strategies for water infrastructure include structural and non-structural approaches. These may include changes in system operations and/or demand management changes, adopting water conserving plumbing codes, and improving flood forecasts, telecommunications, and early warning systems[164] that focus on both adapting physical structures and innovative management.[106,132,165] Such strategies could take advantage of conventional ("gray") infrastructure upgrades (like raising flood control levees); adjustments to reservoir operating rules; new demand management and incentive strategies; land-use management that enhances adaptive capacity; protection and restoration at the scale of river basins, watersheds, and ecosystems; hybrid strategies that blend "green" infrastructure with gray infrastructure; and pricing strategies.[1,106,132,166,167] Green infrastructure approaches that are increasingly being implemented by municipalities across the country include green roofs, rain gardens, roadside plantings, porous pavement, and rainwater harvesting (Ch. 28: Adaptation). These techniques typically utilize soils and vegetation in the built environment to absorb runoff close to where it falls, limiting flooding and sewer backups.[168] There are numerous non-infrastructure related adaptation strategies, some of which could include promoting drought-resistant crops, flood insurance reform, and building densely developed areas away from highly vulnerable areas.

In addition to physical adaptation, capacity-building activities can build knowledge and enhance communication and collaboration within and across sectors.[1,167,169] In particular, building networks, partnerships, and support systems has been identified as a major asset in building adaptive capacity (Ch. 26: Decision Support; Ch. 28: Adaptation).[170]

In addition to stressing the physical infrastructure of water systems, future impacts of climate change may reveal the weaknesses in existing water law regimes to accommodate novel and dynamic water management conditions. The basic paradigms of environmental and natural resources law are preservation and restoration, both of which are based on the assumption that natural systems fluctuate within an unchanging envelope of variability ("stationarity").[171] However, climate change is now projected to affect water supplies during the multi-decade lifetime of major water infrastructure projects in wide-ranging and pervasive ways.[132] Under these circumstances, stationarity will no longer be reliable as the central assumption in water-resource risk assessment and planning.[42,171] For example, in the future, water rights administrators may find it necessary to develop more flexible water rights systems conditioned to address the uncertain impacts of climate change.[172] Agencies and courts may seek added flexibility in regulations and laws to achieve the highest and best uses of limited water resources and to enhance water management capacity in the context of new and dynamic conditions.[132,173]

In the past few years, many federal, state, and local agencies and tribal governments have begun to address climate change adaptation, integrating it into existing decision-making, planning, or infrastructure-improvement processes (Ch. 28: Adaptation).[43,174] Drinking water utilities are increasingly utilizing climate information to prepare assessments of their supplies,[175] and utility associations and alliances, such as the Water Research Foundation and Water Utility Climate Alliance, have undertaken original research to better understand the implications of climate change on behalf of some of the largest municipal water utilities in the United States.[119,156,176]

The economic, social, and environmental implications of climate change induced water cycle changes are very significant, as is the cost of inaction. Adaptation responses need to address considerable uncertainties in the short-, medium-, and long-term; be proactive, integrated, and iterative; and be developed through well-informed stakeholder decision processes functioning within a flexible institutional and legal environment.

3: WATER RESOURCES

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3: WATER RESOURCES

SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages:

The chapter author team engaged in multiple technical discussions via teleconferences from March – June 2012. These discussions followed a thorough review of the literature, which included an inter-agency prepared foundational document,[1] over 500 technical inputs provided by the public, as well as other published literature. The author team met in Seattle, Washington, in May 2012 for expert deliberation of draft key messages by the authors wherein each message was defended before the entire author team before this key message was selected for inclusion in the Chapter. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities." Key messages were further refined following input from the NCADAC report integration team and authors of Ch. 2: Our Changing Climate.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions. Very heavy precipitation events have increased nationally and are projected to increase in all regions. The length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 2: Our Changing Climate, Ch. 20: Southwest, other technical input reports,[2] and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications describe precipitation trends (Ch. 2: Our Changing Climate)[4,7,8,34] and river-flow trends.[13,41] As discussed in Chapter 2, the majority of projections available from climate models (for example, Orlowsky and Seneviratne 2012;[3] Kharin et al. 2013[5]) indicate small projected changes in total average annual precipitation in many areas, while heavy precipitation[6] and the length of dry spells are projected to increase across the entire country. Projected precipitation responses (such as changing extremes) to increasing greenhouse gases are robust in a wide variety of models and depictions of climate.

The broad observed trends of precipitation and river-flow increases have been identified by many long-term National Weather Service (NWS)/National Climatic Data Center (NCDC) weather monitoring networks, USGS streamflow monitoring networks, and analyses of records therefrom (Ch. 2: Our Changing Climate;[34,36,37]). Ensembles of climate models[3,42](see also Ch. 2: Our Changing Climate, Ch. 20: Southwest) are the basis for the reported projections.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings from the 2009 National Climate Assessment.[177]

Observed trends: Precipitation trends are generally embedded amidst large year-to-year natural variations and thus trends may be difficult to detect, may differ from site to site, and may be reflections of multi-decadal variations rather than external (human) forcings. Consequently, careful analyses of longest-term records from many stations across the country and addressing multiple potential explanations are required and are cornerstones of the evidentiary studies described above.

Efforts are underway to continually improve the stability, placement, and numbers of weather observations needed to document trends; scientists also regularly search for other previously unanalyzed data sources for use in testing these findings.

Projected trends: The complexity of physical processes that result in precipitation and runoff reduces abilities to represent or predict them as accurately as would be desired and with the spatial and temporal resolution required for many applications; however, as noted, the trends at the scale depicted in this message are very robust among a wide variety of climate models and projections, which lends confidence that the projections are appropriate lessons from current climate (and streamflow) models. Nonetheless, other influences not included in the climate change projections might influence future patterns of precipitation and runoff, including changes in land cover, water use (by humans and vegetation), and streamflow management.

Climate models used to make projections of future trends are continually increasing in number, resolution, and in the number of additional external and internal influences that might be confounding current projections. For example, much more of all three of these directions for improvement are already evident in projection archives for the next IPCC assessment.

Assessment of confidence based on evidence

Observed trends have been demonstrated by a broad range of methods over the past 20+ years based on best available data; projected precipitation and river-flow responses to greenhouse gas increases are robust across large majorities of available climate (and hydrologic) models from scientific teams around the world.

Confidence is therefore judged to be **high** that annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions.

Confidence is **high** that very heavy precipitation events have increased nationally and are projected to increase in all regions.

Confidence is **high** that the length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States.

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

Short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 16: Northeast, Ch 17: Southeast, Ch. 2: Our Changing Climate, Ch. 18: Midwest, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 21: Northwest, Ch. 23: Hawai'i and Pacific Islands, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Projected drought trends derive directly from climate models in some studies (for example, Hoerling et al. 2012;[8] Wehner et al. 2011;[30] Gao et al. 2012;[32] Gao et al. 2011;[33]), from hydrologic models responding to projected climate trends in others (for example, Georgakakos and Zhang 2011;[38] Cayan et al. 2010;[48]), from considerations of the interactions between precipitation deficits and either warmer or cooler temperatures in historical (observed) droughts,[48] and from combinations of these approaches (for example, Trenberth et al. 2004[49]) in still other studies.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings from the 2009 National Climate Assessment.[177]

Warmer temperatures are robustly projected by essentially all climate models, with what are generally expected to be directly attendant increases in the potentials for greater evapotranspiration, or ET (although it is possible that current estimates of future ET are overly influenced by temperatures at the expense of other climate variables, like wind speed, humidity, net surface radiation, and soil moisture that might change in ways that could partly ameliorate rising ET demands). As a consequence, there is a widespread expectation that more water from precipitation will be evaporated or transpired in the warmer future, so that except in regions where precipitation increases more than ET increases, less overall water will remain on the landscape and droughts will intensify and become more common. Another widespread expectation is that precipitation variability will increase, which may result in larger swings in moisture availability, with swings towards the deficit side resulting in increased frequencies and intensities of drought conditions on seasonal time scales to times scales of multiple decades. An important remaining uncertainty, discussed in the supporting text for Key Message #1, is the extent to which the types of models used to project future droughts may be influencing results with a notable recent tendency for studies with more complete, more resolved land-surface models, as well as climate models, to yield more moderate projected changes.

Other uncertainties derive from the possibility that changes in other variables or influences of CO_2-fertilization and/or land cover change may also partly ameliorate drought intensification. Furthermore in many parts of the country, El Niño-Southern Oscillation (and other oceanic) influences on droughts and floods are large, and can overwhelm climate change effects during the next few decades. At present, however, the future of these oceanic climate influences remains uncertain.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

Confidence is judged to be **medium-high** that short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Confidence is **high** that longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast.

Key Message #3 Traceable Account

Flooding may intensify in many U.S. regions, even in areas where total precipitation is projected to decline.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 16: Northeast, Ch 17: Southeast, Ch. 2: Our Changing Climate, Ch. 18: Midwest, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 21: Northwest, Ch. 23: Hawai'i and Pacific Islands, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

The principal observational bases for the key message are careful national-scale flood-trend analyses[58] based on annual peak-flow records from a selection of 200 USGS streamflow gaging stations measuring flows from catchments that are minimally influenced by upstream water uses, diversions, impoundments, or land-use changes with more than 85 years of records, and analyses of two other subsets of USGS gages with long records (including gages both impacted by human activities and less so), including one analysis of 50 gages nationwide[56] and a second analysis of 572 gages in the eastern United States.[57] There is some correspondence among regions with significant changes in annual precipitation (Ch. 2: Our Changing Climate) and soil moisture (Figures 3.2 and 3.3), and annual flood magnitudes (Figure 3.5).[58]

Projections of future flood-frequency changes result from detailed hydrologic models (for example, Das et al. 2012;[60] Raff et al. 2009;[133]Walker et al. 2011[135]) of rivers that simulate responses to projected precipitation and temperature changes from climate models; such simulations have only recently begun to emerge in the peer-reviewed literature.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings from the 2009 National Climate Assessment.[177]

Large uncertainties remain in efforts to detect flood-statistic changes attributable to climate change, because a wide range of local factors (such as dams, land-use changes, river channelization) also affect flood regimes and can mask, or proxy for, climate change induced alterations. Furthermore, it is especially difficult to detect any kinds of trends in what are, by definition, rare and extreme events. Finally, the response of floods to climate changes are expected to be fairly idiosyncratic from basin to basin, because of the strong influences of within-storm variations and local, basin-scale topographic, soil and vegetation, and river network characteristics that influence the size and extent of flooding associated with any given storm or season.[54,55,56,57]

Large uncertainties still exist as to how well climate models can represent and project future extremes of precipitation. This has – until recently – limited attempts to make specific projections of future flood frequencies by using climate model outputs directly or as direct inputs to hydrologic models. However, precipitation extremes are expected to intensify as the atmosphere warms, and many floods result from larger portions of catchment areas receiving rain as snowlines recede upward. As rain runs off more quickly than snowfall this results in increased flood potential; furthermore, occasional rain-on-snow events exacerbates this effect. This trend is broadly expected to increase in frequency under general warming trends, particularly in mountainous catchments.[62] Rising sea levels and projected increase in hurricane-associated storm intensity and rainfall rates provide first-principles bases for expecting intensified flood regimes in coastal settings (see Ch. 2: Our Changing Climate).

Assessment of confidence based on evidence

Future changes in flood frequencies and intensities will depend on a complex combination of local to regional climatic influences, and the details of complex surface-hydrologic conditions in each catchment (for example, topography, land cover, and upstream management). Consequently, flood frequency changes may be neither simple nor regionally homogeneous, and basin by basin projections may need to be developed. Early results now appearing in the literature have most often projected intensifications of flood regimes, in large part as responses to projections of more intense storms and increasingly rainy (rather than snowy) storms in previously snow-dominated settings. Confidence in current estimates of future changes in flood frequencies and intensities is overall judged to be **low**.

Key Message #4 Traceable Account

Climate change is expected to affect water demand, groundwater withdrawals, and aquifer recharge, reducing groundwater availability in some areas.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] regional chapters of the NCA, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Several recent studies[65,66,67,68,71,72] have evaluated the potential impacts of changes in groundwater use and recharge under scenarios including climate change, and generally they have illustrated the common-sense conclusion that changes in pumpage can have immediate and significant effects in the nation's aquifers. This has certainly been the historical experience in most aquifers that have seen significant development; pumpage variations usually tend to yield more immediate and often larger changes on many aquifers than do historical climate variations on time scales from years to decades. Meanwhile, for aquifers in the Southwest, there is a growing literature of geochemical studies that fingerprint various properties of groundwater and that are demonstrating that most western groundwater derives preferentially from snowmelt, rather than rainfall or other sources.[50,51,66,74] This finding suggests that much western recharge may be at risk of changes and disruptions from projected losses of snowpack, but as yet provides relatively little indication whether the net effects will be recharge declines, increases, or simply spatial redistribution.

New information and remaining uncertainties

The precise responses of groundwater storage and flow to climate change are not well understood, but recent and ongoing studies provide insights on underlying mechanisms.[65,66,67] The observations and modeling evidence to make projections of future responses of groundwater recharge and discharge to climate change are thus far very limited, primarily because of limitations in data availability and in the models themselves. New forms and networks of observations and new modeling approaches and tools are needed to provide projections of the likely influences of climate changes on groundwater recharge and discharge. Despite the uncertainties about the specifics of climate change impacts on groundwater, impacts of reduced groundwater supply and quality would likely be detrimental to the nation.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is judged to be **high** that climate change is expected to affect water demand, groundwater withdrawals, and aquifer recharge, reducing groundwater availability in some areas.

KEY MESSAGE #5 TRACEABLE ACCOUNT

Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands.

Description of evidence base

This message has a strong theoretical and observational basis, including considerable historical experience with seawater intrusion into many of the nation's coastal aquifers and wetlands under the influence of heavy pumpage, some experience with the influences of droughts and storms on seawater intrusion, and experience with seepage of seawater into shallow coastal aquifers under storm and storm surge conditions that lead to coastal inundations with seawater. The likely influences of sea level rise on seawater intrusion into coastal (and island) aquifers and wetlands are somewhat less certain, as discussed below, although it is projected that sea level rise may increase opportunities for saltwater intrusion (see Ch. 25: Coasts).

New information and remaining uncertainties

There are few published studies describing the kinds of groundwater quality and flow modeling that are necessary to assess the real-world potentials for sea level rise to affect seawater intrusion.[78] Studies in the literature and historical experience demonstrate the detrimental impacts of alterations to the water budgets of the freshwater lenses in coastal aquifers and wetlands around the world (most often by groundwater development), but few evaluate the impacts of sea level rise alone. More studies with real-world aquifer geometries and development regimes are needed to reduce the current uncertainty of the potential interactions of sea level rise and seawater intrusion.

Assessment of confidence based on evidence

Confidence is **high** that sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands.

KEY MESSAGE #6 TRACEABLE ACCOUNT

Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and other pollutant loads.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 8: Ecosystems, Ch. 15: Biogeochemical Cycles, and over 500 technical inputs on a wide range of topics that were reviewed as part of the Federal Register Notice solicitation for public input.

Thermal stratification of deep lakes and reservoirs has been observed to increase with increased air and water temperatures,[1,81,82] and may be eliminated in shallow lakes. Increased stratification reduces mixing, resulting in reduced oxygen in bottom waters. Deeper set-up of vertical thermal stratification in lakes and reservoirs may reduce or eliminate a bottom cold water zone; this, coupled with lower oxygen concentration, results in a degraded aquatic ecosystem.

Major precipitation events and resultant water flows increase watershed pollutant scour and thus increase pollutant loads.[84] Fluxes of mineral weathering products (for example, calcium, magnesium, sodium, and silicon) have also been shown to increase in response to higher discharge.[86] In the Mississippi drainage basin, increased precipitation has resulted in increased nitrogen loads contributing to hypoxia in the Gulf of Mexico.[85] Models predict and observations confirm that continued warming will have increasingly negative effects on lake water quality and ecosystem health.[81]

Future re-mobilization of sediment stored in large river basins will be influenced by changes in flood frequencies and magnitudes, as well as on vegetation changes in the context of climate and other anthropogenic factors.[87] Model projections suggest that changes in sediment delivery will vary regionally and by land-use type, but on average could increase by 25% to 55%.[88]

New information and remaining uncertainties

It is unclear whether increasing floods and droughts cancel each other out with respect to long-term pollutant loads.

It is also uncertain whether the absolute temperature differential with depth will remain constant, even with overall lake and reservoir water temperature increases. Further, it is uncertain if greater mixing with depth will eliminate thermal stratification in shallow, previously stratified lakes. Although recent studies of Lake Tahoe provide an example of longer stratification seasons,[83] lakes in other settings and with other geometries may not exhibit the same response.

Many factors influence stream water temperature, including air temperature, forest canopy cover, and ratio of baseflow to streamflow.

Assessment of confidence based on evidence

Given the evidence base, confidence is **medium** that increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and pollutant loads.

KEY MESSAGE #7 TRACEABLE ACCOUNT

Climate change affects water demand and the ways water is used within and across regions and economic sectors. The Southwest, Great Plains, and Southeast are particularly vulnerable to changes in water supply and demand.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 2: Our Changing Climate, Ch. 17: Southeast, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 23: Hawai'i and Pacific Islands, and many technical inputs on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

Observed Trends: Historical water withdrawals by sector (for example, municipal, industrial, agricultural, and thermoelectric) have been monitored and documented by USGS for over 40 years and represent a credible database to assess water-use trends, efficiencies, and underlying drivers. Water-use drivers principally include population, personal income, electricity consumption, irrigated area, mean annual temperature, growing season precipitation, and growing season potential evapotranspiration.[99] Water-use efficiencies are also affected by many non-climate factors, including demand management, plumbing codes, water efficient appliances, efficiency improvement programs, and pricing strategies;[100] changes from water intensive manufacturing and other heavy industrial activities to service-oriented businesses,[101] and enhanced water-use efficiencies in response to environmental pollution legislation; replacement of older once-through-cooling electric power plants by plants that recycle their cooling water; and switching from flood irrigation to more efficient methods in the western United States.[102]

Projected Trends and Consequences: Future projections have been carried out with and without climate change to first assess the water demand impacts of projected population and socioeconomic increases, and subsequently combine them with climate change induced impacts. The main findings are that in the absence of climate change total water withdrawals in the U.S. will increase by 3% in the coming 50 years,[99] with approximately half of the U.S. experiencing a total water demand decrease and half an increase. If, however, climate change projections are also factored in, the demand for total water withdrawals is projected to rise by an average of 26%,[99] with more than 90% of the U.S. projected to experience a total demand increase, and decreases projected only in parts of the Midwest, Northeast, and Southeast. When coupled with the observed and projected drying water cycle trends (see key messages in "Climate Change Impacts on the Water Cycle" section), the water demand impacts of projected population, socioeconomic, and climate changes intensify and compound in the Southwest and Southeast, rendering these regions particularly vulnerable in the coming decades.

New information and remaining uncertainties

The studies of water demand in response to climate change and other stressors are very recent and constitute new information on their own merit.[99] In addition, for the first time, these studies make it possible to piece together the regional implications of climate change induced water cycle alterations in combination with projected changes in water demand. Such integrated assessments also constitute new information and knowledge building.

Demand projections include various uncertain assumptions which become increasingly important in longer term (multi-decadal) projections. Because irrigation demand is the largest water demand component most sensitive to climate change, the most important climate-related uncertainties are precipitation and potential evapotranspiration over the growing season. Non-climatic uncertainties relate to future population distribution, socioeconomic changes, and water-use efficiency improvements.

Assessment of confidence based on evidence

Considering that (a) droughts are projected to intensify in large areas of the Southwest, Great Plains, and the Southeast, and (b) that these same regions have experienced and are projected to experience continuing population and demand increases, confidence that these regions will become increasingly vulnerable to climate change is judged to be **high**.

KEY MESSAGE #8 TRACEABLE ACCOUNT

Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. These trends are expected to continue, increasing the likelihood of water shortages for many uses.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 2: Our Changing Climate, Ch. 17: Southeast, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 23: Hawai'i and Pacific Islands, and over 500 technical inputs on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

Observed Trends: Observations suggest that the water cycle in the Southwest, Great Plains, and Southeast has been changing toward drier conditions (Ch. 17: Southeast).[130,151,152] Furthermore, paleoclimate tree-ring reconstructions indicate that drought in previous centuries has been more intense and of longer duration than the most extreme drought of the 20th and 21st centuries.[40]

Projected Trends and Consequences: Global Climate Model (GCM) projections indicate that this trend is likely to persist, with runoff reductions (in the range of 10% to 20% over the next 50 years) and intensifying droughts.[48]

The drying water cycle is expected to affect all human and ecological water uses, especially in the Southwest. Decreasing precipitation, rising temperatures, and drying soils are projected to increase irrigation and outdoor watering demand (which account for nearly 90% of consumptive water use) by as much as 34% by 2060 under the A2 emissions scenario.[99] Decreasing runoff and groundwater recharge are expected to reduce surface and groundwater supplies,[66] increasing the annual risk of water shortages from 25% to 50% by 2060.[130] Changes in streamflow timing will increase the mismatch of supply and demand. Earlier and declining streamflow and rising demands will make it more difficult to manage reservoirs, aquifers, and other water infrastructure.[130]

Such impacts and consequences have been identified for several southwestern and western river basins including the Colorado,[38] Rio Grande,[126] and Sacramento-San Joaquin.[127,128,129]

New information and remaining uncertainties

The drying climate trend observed in the Southwest and Southeast in the last decades is consistent across all water cycle variables (precipitation, temperature, snow cover, runoff, streamflow, reservoir levels, and soil moisture) and is not debatable. The debate is over whether this trend is part of a multi-decadal climate cycle and whether it will reverse direction at some future time. However, the rate of change and the comparative GCM assessment results with and without historical CO_2 forcing (Ch. 2: Our Changing Climate) support the view that the observed trends are due to both factors acting concurrently.

GCMs continue to be uncertain with respect to precipitation, but they are very consistent with respect to temperature. Runoff, streamflow, and soil moisture depend on both variables and are thus less susceptible to GCM precipitation uncertainty. The observed trends and the general GCM agreement that the southern states will continue to experience streamflow and soil moisture reductions[34,41] provides confidence that these projections are robust.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **high** that changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. Confidence is **high** that these trends are expected to continue, increasing the likelihood of water shortages for many uses.

KEY MESSAGE #9 TRACEABLE ACCOUNT

Increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the U.S.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 2: Our Changing Climate, Ch. 21: Northwest, Ch. 19: Great Plains, Ch. 18: Midwest, Ch. 16: Northeast, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Observed Trends: Very heavy precipitation events have intensified in recent decades in most U.S. regions, and this trend is projected to continue (Ch. 2: Our Changing Climate). Increasing heavy precipitation is an important contributing factor for floods, but flood magnitude changes also depend on specific watershed conditions (including soil moisture, impervious area, and other human-caused alterations). There is, however, some correspondence among regions with significant changes in annual precipitation (Ch. 2: Our Changing Climate), soil moisture (Figures 3.2 and 3.3), and annual flood magnitudes (Figure 3.5).[58]

Flooding and seawater intrusion from sea level rise and increasing storm surge threaten New York, Boston, Philadelphia, Virginia Beach, Wilmington, Charleston, Miami, Tampa, Naples, Mobile, Houston, New Orleans, and many other coastal cities (Chapter 25: Coasts).

Projected Trends: Projections of future flood-frequency changes result from detailed hydrologic[60,133,135] and hydraulic models of rivers that simulate responses to projected precipitation and temperature changes from climate models.

Consequences: Floods already affect human health and safety and result in substantial economic, ecological, and infrastructure damages. Many cities are located along coasts and, in some of these cities (including New York, Boston, Miami, Savannah, and New Orleans), sea level rise is expected to exacerbate coastal flooding issues by backing up flood flows and impeding flood-management responses (see Ch. 16: Northeast and Ch. 25: Coasts).[136]

Projected changes in flood frequency and severity can bring new challenges in flood risk management. For urban areas in particular, flooding impacts critical infrastructure in ways that are difficult to foresee and can result in interconnected and cascading failures (for example, failure of electrical generating lines can cause pump failure, additional flooding, and failure of evacuation services). Increasing likelihood of flooding also brings with it human health risks associated with failure of critical infrastructure (Ch. 11: Urban),[137] from waterborne disease that can persist well beyond the occurrence of very heavy precipitation (Ch. 9: Human Health),[139] from water outages associated with infrastructure failures that cause decreased sanitary conditions,[138] and from ecosystem changes that can affect airborne diseases (Ch. 8: Ecosystems).[140]

New information and remaining uncertainties

Large uncertainties still exist as to how well climate models can represent and project future precipitation extremes. However, precipitation extremes are expected to intensify as the atmosphere warms, and many floods result from larger portions of catchment areas receiving rain as snowlines recede upward. As rain runs off more quickly than snowfall, this results in increased flood potential; furthermore occasional rain-on-snow events exacerbate this effect. This trend is broadly expected to increase in frequency under general warming trends, particularly in mountainous catchments.[62]

Assessment of confidence based on evidence

Future changes in flood frequencies and intensities will depend on a complex combination of local to regional climatic influences and on the details of complex surface-hydrologic conditions in each catchment (for example, topography, land cover, and upstream managements). Consequently, flood frequency changes may be neither simple nor regionally homogeneous, and basin by basin projections may need to be developed. Nonetheless, early results now appearing in the literature have most often projected intensifications of flood regimes, in large part as responses to projections of more intense storms and more rainfall runoff from previously snowbound catchments and settings.

Therefore, confidence is judged to be **medium** that increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the U.S.

KEY MESSAGE #10 TRACEABLE ACCOUNT

In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed within existing practices.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] other chapters of the NCA, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Observed and Projected Trends: Many U.S. regions are facing critical water management and planning challenges. Recent assessments illustrate water management challenges facing California,[127,128,129,149] the Southwest,[130,151] Southeast (Ch. 17: Southeast),[136,152] Northwest,[153] Great Plains,[154] and Great Lakes.[155]

The Sacramento-San Joaquin Bay Delta is already threatened by flooding, seawater intrusion, and changing needs for environmental, municipal, and agricultural water uses. Managing these risks and uses requires reassessment of a very complex system of water rights, levees, stakeholder consensus processes, reservoir system operations, and significant investments, all of which are subject to large uncertainties.[54,148] Given the projected climate changes in the Sacramento-San Joaquin Bay Delta, adherence to historical management and planning practices may not be a long-term viable option,[128,129] but the supporting science is not yet fully actionable,[42] and a flexible legal and policy framework embracing change and uncertainty is lacking.

The Apalachicola-Chattahoochee-Flint (ACF) River basin in Georgia, Alabama, and Florida supports a wide range of water uses and the regional economy, creating challenging water-sharing tradeoffs for the basin stakeholders. Climate change presents new stresses and uncertainties.[152] ACF stakeholders are working to develop a management plan that balances economic, ecological, and social values.[160]

New information and remaining uncertainties

Changes in climate, water demand, land use, and demography combine to challenge water management in unprecedented ways. This is happening with a very high degree of certainty in most U.S. regions. Regardless of its underlying causes, climate change poses difficult challenges for water management because it invalidates stationarity – the perception that climate varies around a predictable mean based on the experience of the last century – and increases hydrologic variability and uncertainty. These conditions suggest that past management practices will become increasingly ineffective and that water management can benefit by the adoption of iterative, risk-based, and adaptive approaches.

Assessment of confidence based on evidence

The water resources literature is unanimous that water management should rely less on historical practices and responses and more on robust, risk-based, and adaptive decision approaches.

Therefore confidence is **very high** that in most U.S. regions, water resources managers and planners will face new risks, vulnerabilities, and opportunities that may not be properly managed with existing practices.

KEY MESSAGE #11 TRACEABLE ACCOUNT

Increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts. Many institutional, scientific, economic, and political barriers present challenges to implementing adaptive strategies.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document[1] and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

There are many examples of adaptive strategies for water infrastructure[106,132,164,165] as well as strategies for demand management, land-use and watershed management, and use of "green" infrastructure.[1,106,132,166,167]

Building adaptive capacity ultimately increases the ability to develop and implement adaptation strategies and is considered a no-regrets strategy.[1,169] Building networks, partnerships, and support systems has been identified as a major asset in building adaptive capacity (Ch. 26: Decision Support; Ch. 28: Adaptation).[170]

Water utility associations have undertaken original research to better understand the implications of climate change on behalf of some of the largest municipal water utilities in the United States.[119,156,176]

Challenges include "stationarity" no longer being reliable as the central assumption in water-resource planning,[171] considerable uncertainties, insufficient actionable science ready for practical application, the challenges of stakeholder engagement, and a lack of agreement on "post-stationarity" paradigms on which to base water laws, regulations, and policies.[42] Water administrators may find it necessary to develop more flexible water rights and regulations.[132,172,173]

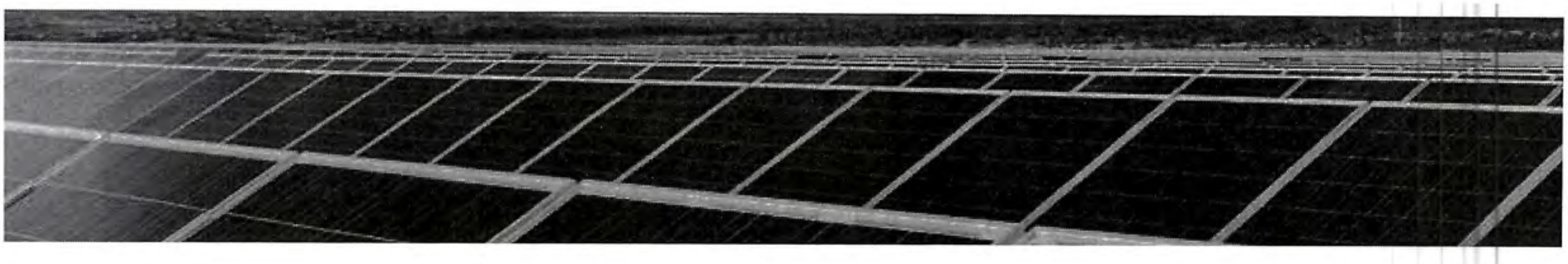
New information and remaining uncertainties

Jurisdictions at the state and local levels are addressing climate change related legal and institutional issues on an individual basis. An ongoing assessment of these efforts may show more practical applications.

Assessment of confidence based on evidence

Confidence is **very high** that increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts.

Confidence is **very high** that many institutional, scientific, economic, and political barriers present challenges to implementing adaptive strategies.



Climate Change Impacts in the United States

CHAPTER 4
ENERGY SUPPLY AND USE

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On the Web: http://nca2014.globalchange.gov/report/sectors/energy

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

4
ENERGY SUPPLY AND USE

KEY MESSAGES

1. **Extreme weather events are affecting energy production and delivery facilities, causing supply disruptions of varying lengths and magnitudes and affecting other infrastructure that depends on energy supply. The frequency and intensity of certain types of extreme weather events are expected to change.**
2. **Higher summer temperatures will increase electricity use, causing higher summer peak loads, while warmer winters will decrease energy demands for heating. Net electricity use is projected to increase.**
3. **Changes in water availability, both episodic and long-lasting, will constrain different forms of energy production.**
4. **In the longer term, sea level rise, extreme storm surge events, and high tides will affect coastal facilities and infrastructure on which many energy systems, markets, and consumers depend.**
5. **As new investments in energy technologies occur, future energy systems will differ from today's in uncertain ways. Depending on the character of changes in the energy mix, climate change will introduce new risks as well as opportunities.**

The U.S. energy supply system is diverse and robust in its ability to provide a secure supply of energy with only occasional interruptions. However, projected impacts of climate change will increase energy use in the summer and pose additional risks to reliable energy supply. Extreme weather events and water shortages are already interrupting energy supply, and impacts are expected to increase in the future. Most vulnerabilities and risks to energy supply and use are unique to local situations; others are national in scope.

In addition to being vulnerable to the effects of climate change, electricity generation is a major source of the heat-trapping gases that contribute to climate change. Therefore, regulatory or policy efforts aimed at reducing emissions would also affect the energy supply system. See Ch. 10: Energy, Water, and Land, Key Message 2; and Ch. 27: Mitigation for more on this topic. This chapter focuses on impacts of climate change to the energy sector.

Energy infrastructure around the country has been compromised by extreme weather events.

The impacts of climate change in other countries will also affect U.S. energy systems through global and regional cross-border markets and policies. Increased energy demand within global markets due to industrialization, population growth, and other factors will influence U.S. energy costs through competition for imported and exported energy products. The physical impacts of climate change on future energy systems in the 25- to 100-year timeframe will depend on how those energy systems evolve. That evolution will be driven by multiple factors, including technology innovations and carbon emission constraints.

Adaptation actions can allow energy infrastructure to adjust more readily to climate change. Many investments toward adaptation provide short-term benefits because they address current vulnerabilities as well as future risks, and thus entail "no regrets." Such actions can include a focus on increased efficiency of energy use as well as improvements in the reliability of production and transmission of energy. The general concept of adaptation is presented in Chapter 28: Adaptation.

Key Message 1: Disruptions from Extreme Weather

Extreme weather events are affecting energy production and delivery facilities, causing supply disruptions of varying lengths and magnitudes and affecting other infrastructure that depends on energy supply. The frequency and intensity of certain types of extreme weather events are expected to change.

Much of America's energy infrastructure is vulnerable to extreme weather events. Because so many components of U.S. energy supplies – like coal, oil, and electricity – move from one area to another, extreme weather events affecting energy infrastructure in one place can lead to supply consequences elsewhere.

Climate change has begun to affect the frequency, intensity, and length of certain types of extreme weather events.[1,2,3] What is considered an extreme weather or climate event varies from place to place. Observed changes across most of the U.S. include increased frequency and intensity of extreme precipitation events, sustained summer heat, and in some regions, droughts and winter storms. The frequency of cold waves has decreased (Ch. 2: Our Changing Climate).

Projected climate changes include increases in various types of extreme weather events, particularly heat waves, wildfire, longer and more intense drought, more frequent and intense very heavy precipitation events, and extreme coastal high water due to heavy-precipitation storm events coupled with sea level rise. Extreme coastal high water will increasingly disrupt infrastructure services in some locations.[4] The frequency of cold waves is expected to continue decreasing. Disruptions in services in one infrastructure system (such as energy) will lead to disruptions in one or more other infrastructures (such as communications and transportation) that depend on other affected systems. Infrastructure exposed to extreme weather and also stressed by age or by demand that exceeds designed levels is particularly vulnerable (see Ch. 11: Urban).

Like much of the nation's infrastructure affected by major weather events with estimated economic damages greater than $1 billion,[5,6] U.S. energy facilities and systems, especially those located in coastal areas, are vulnerable to extreme weather events. Wind and storm surge damage by hurricanes already causes significant infrastructure losses on the Gulf Coast.

In 2005, damage to oil and gas production and delivery infrastructure by Hurricanes Katrina and Rita affected natural gas, oil, and electricity markets in most parts of the United States.[4,7] Market impacts were felt as far away as New York and New England,[8,9] highlighting the significant indirect economic impacts of climate-related events that go well beyond the direct damages to energy infrastructure.

Various aspects of climate change will affect and disrupt energy distribution and energy production systems. It is projected that wildfires will affect extensive portions of California's electricity transmission grid.[10] Extreme storm surge events at high tides are expected to increase,[11] raising the risk of inundating energy facilities such as power plants, refineries, pipelines, and transmission and distribution networks. Rail transportation lines that carry coal to power plants, which produced 42% of U.S. electricity in 2011, often follow riverbeds. More intense rainstorms can lead to river flooding that degrades or washes out nearby railroads and roadbeds, and increases in rainstorm intensity have been observed and are projected to continue.

Paths of Hurricanes Katrina and Rita Relative to Oil and Gas Production Facilities

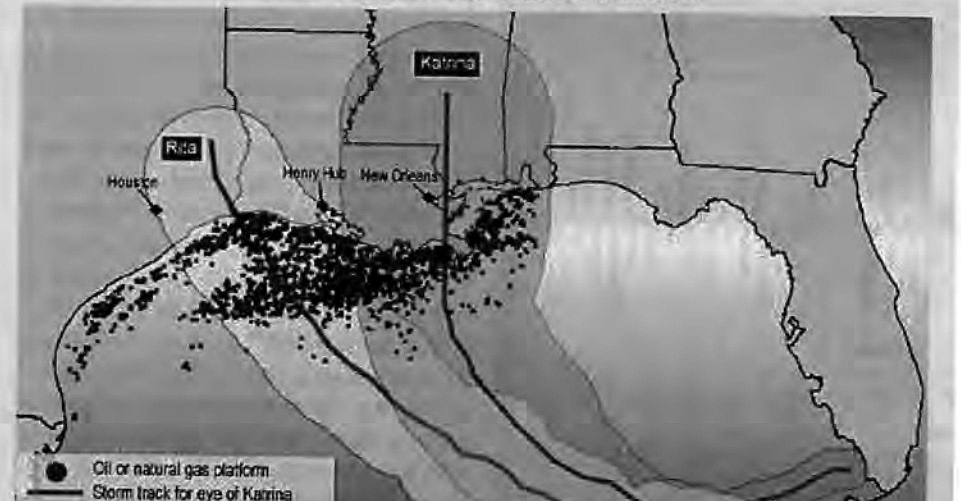


Figure 4.1. A substantial portion of U.S. energy facilities is located on the Gulf Coast as well as offshore in the Gulf of Mexico, where they are particularly vulnerable to hurricanes and other storms and sea level rise. (Figure source: U.S. Government Accountability Office 2006).

By learning from previous events, offshore operations can be made more resilient to the impacts of hurricanes. During Hurricane Isaac in August 2012, the U.S. Bureau of Safety and Environmental Enforcement reported that oil and gas production was safely shut down and restarted within days of the event.[12]

The geographical diversification of energy sources away from hurricane-prone areas such as the Gulf of Mexico has reduced vulnerability to hurricanes. The U.S. Energy Information Administration (EIA) reports that the percentage of natural gas production from the Gulf of Mexico shifted from 20% in 2005 to 7% in 2012.[13] This is due to the development of shale gas production in other parts of the United States.

Key Message 2: Climate Change and Seasonal Energy Demands

Higher summer temperatures will increase electricity use, causing higher summer peak loads, while warmer winters will decrease energy demands for heating. Net electricity use is projected to increase.

Over the last 20 years, annual average temperatures typically have been higher than the long-term average; nationally, temperatures were above average during 12 of the last 14 summers (Ch. 2: Our Changing Climate).[2] These increased temperatures are already affecting the demand for energy needed to cool buildings in the United States.

Average temperatures have increased in recent decades. In response, the Energy Information Administration began using 10-year average weather data instead of 30-year average weather data in order to estimate energy demands for heating and cooling purposes. The shorter period is more consistent with the observed trend of warmer winters and summers,[14] but is still not necessarily optimal for anticipating near-term temperatures.[17]

While recognizing that many factors besides climate change affect energy demand (including population changes, economic conditions, energy prices, consumer behavior, conservation programs, and changes in energy-using equipment), increases in temperature will result in increased energy use for cooling and decreased energy use for heating. These impacts differ among regions of the country and indicate a shift from predominantly heating to predominantly cooling in some regions with moderate climates. For example, in the Northwest, energy demand for cooling is projected to increase over the next century due to population growth, increased cooling degree days, and increased use of air conditioners as people adapt to higher temperatures.[19] Population growth is also expected to increase energy demand for heating. However, the projected increase in energy demand for heating is about half as much when the effects of a warming climate are considered along with population growth.[19]

Demands for electricity for cooling are expected to increase in every U.S. region as a result of increases in average temperatures and high temperature extremes. The electrical grid handles virtually the entire cooling load, while the heating load is distributed among electricity, natural gas, heating oil, passive solar, and biofuel. In order to meet increased demands for peak electricity, additional generation and distribution facilities will be needed, or demand will have to be managed through a variety of mechanisms. Electricity at peak demand typically is more expensive to supply than at average demand.[21] Because the balance between heating and cooling differs by location, the balance of energy use among delivery forms and fuel types will likely shift from natural gas and fuel oil used for heating to electricity used for air conditioning. In hotter conditions, more fuel and energy are required to generate and deliver electricity, so increases in air conditioning use and shifts from heating to cooling in regions with moderate climates will increase primary energy demands.[4]

Increase in Cooling Demand and Decrease in Heating Demand

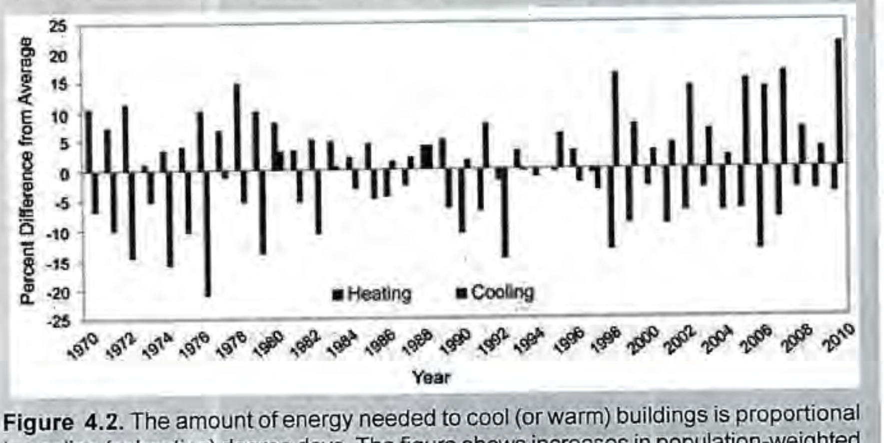


Figure 4.2. The amount of energy needed to cool (or warm) buildings is proportional to cooling (or heating) degree days. The figure shows increases in population-weighted cooling degree days, which result in increased air conditioning use, and decreases in population-weighted heating degree days, meaning less energy required to heat buildings in winter, compared to the average for 1970-2000. Cooling degree days are defined as the number of degrees that a day's average temperature is above 65°F, while heating degree days are the number of degrees a day's average temperature is below 65°F. As shown, the increase in cooling needs is greater than the decrease in heating needs (Data from NOAA NCDC 2012[16]).

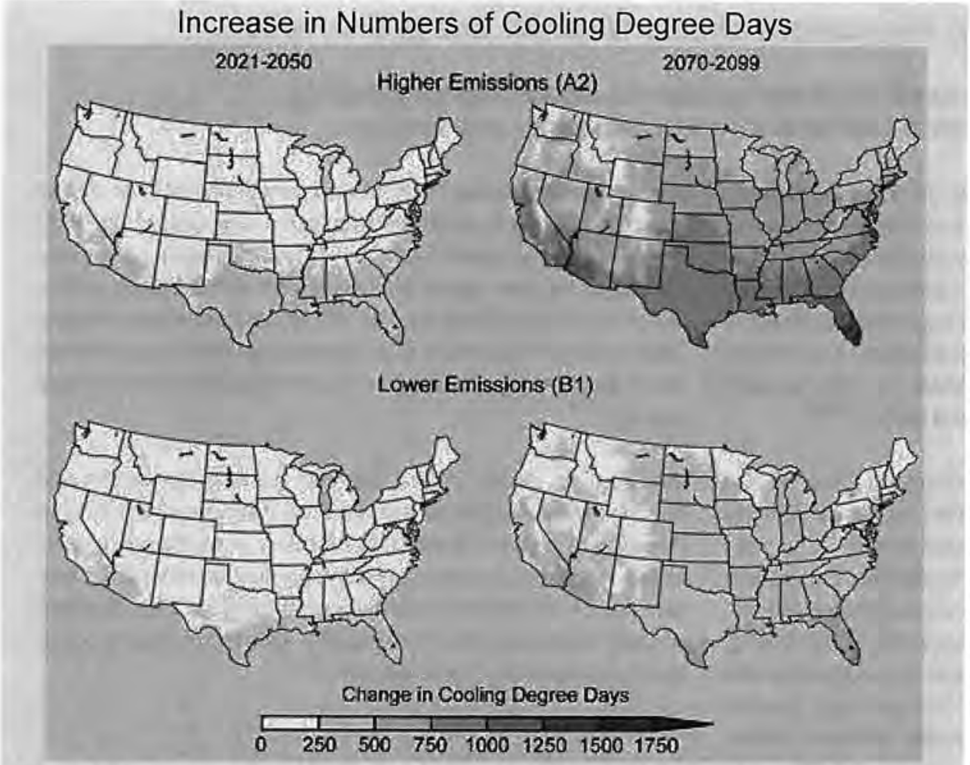


Figure 4.3. These maps show projected average changes in cooling degree days for two future time periods: 2021-2050 and 2070-2099 (as compared to the period 1971-2000). The top panel assumes climate change associated with continued increases in emissions of heat-trapping gases (A2), while the bottom panel assumes significant reductions (B1). The projections show significant regional variations, with the greatest increases in the southern United States by the end of this century under the higher emissions scenario. Furthermore, population projections suggest continued shifts toward areas that require air conditioning in the summer, thereby increasing the impact of temperature changes on increased energy demand.[18] (Figure source: NOAA NCDC / CICS-NC).

Table 4.1. Hotter and longer summers will increase the amount of electricity necessary to run air conditioning, especially in the Southeast and Southwest. Warmer winters will decrease the amount of natural gas required to heat buildings, especially in the Northeast, Midwest, and Northwest. Table information is adapted from multi-model means from 8 NARCCAP regional climate simulations for the higher emissions scenario (A2) considered in this report and is weighted by population. (Source: adapted from Regional Climate Trends and Scenarios reports[20])

Changing Energy Use for Heating and Cooling Will Vary by Region

	Consequences: Challenges and Opportunities	
Region	**Cooling**	**Heating**
Physical Impacts - High Likelihood	**Hotter and Longer Summers** Number of additional extreme hot days (> 95°F) and % increase in cooling degree days per year in 2041-2070 above 1971-2000 level	**Warmer Winters** Number of fewer extreme cold days (< 10°F) and % decrease in heating degree days per year in 2041-2070 below 1971-2000 level
Northeast	+10 days, +77%	-12 days, -17%
Southeast	+23 days, +43%	-2 days, -19%
Midwest	+14 days, +64%	-14 days, -15%
Great Plains	+22 days, +37%	-4 days, -18%
Southwest	+20 days, +44%	-3 days, -20%
Northwest	+5 days, +89%	-7 days, -15%
Alaska	Not studied	Not studied
Pacific Islands	Not studied	Not studied

Climate-related temperature shifts are expected to cause a net increase in residential electricity use.[21,22] Increased electricity demands for cooling will exceed electricity savings resulting from lower energy demands for heating. One study examining state-level energy consumption, weather data, and high emission scenarios (A2 and A1FI; Appendix 3: Climate Science Supplement) found a net increase of 11% in residential energy demand.[23] Another study reported annual increases in net energy expenditures for cooling and heating of about 10% ($26 billion in 1990 U.S. dollars) by the end of this century for 4.5°F of warming, and 22% ($57 billion in 1990 dollars) for overall warming of about 9°F.[24] New energy-efficient technology could help to offset growth in demand.

Several studies suggest that if substantial reductions in emissions of heat-trapping gases were required, the electricity generating sector would switch to using alternative (non-fossil) fuel sources first, given the multiple options available to generate electricity from sources that do not emit heat-trapping gases, such as wind and solar power. Under these circumstances, electricity would displace direct use of fossil fuels for some applications, such as heating, to reduce overall emissions of heat-trapping gases.[25,26] The implications for peak electricity demand could be significant. In California, for example, the estimated increase in use of electricity for space heating would shift the peak in electricity demand from summer to winter.[27] In addition, the fact that electricity from wind and solar is highly variable and may not be available when needed has the potential to decrease the reliability of the electricity system. However, some initial studies suggest that a well-designed electricity system with high penetration of renewable sources of energy should not decrease reliability (for example, Hand et al. 2012[28]).

Key Message 3: Implications of Less Water for Energy Production

Changes in water availability, both episodic and long-lasting, will constrain different forms of energy production.

Producing energy from fossil fuels (coal, oil, and natural gas), nuclear power, biofuels, hydropower, and some solar power systems often requires adequate and sustainable supplies of water. Issues relatableted to water, including availability and restrictions on the temperature of cooling water returned to streams, already pose challenges to production from existing power plants and the ability to obtain permits to build new facilities (Ch. 10: Energy, Water, and Land).[21,29,30]

In the future, long-term precipitation changes, drought, and reduced snowpack are projected to alter water availability (Ch. 3: Water). Recent climate data indicate a national average increase in annual precipitation, owing to significant increases across the central and northeastern portions of the nation and a mix of increases and decreases elsewhere (Ch. 2: Our Changing Climate, Figure 2.12). Projected changes in precipitation are small in most areas of the United States, but vary both seasonally and regionally (Figure 4.4). The number of heavy downpours has generally increased and is projected to increase for all regions (Ch 2: Our Changing Climate, Figures 2.16, 2.17, 2.18, and 2.19).

Different analyses of observed changes in dry spell length do not show clear trends,[31] but longer dry spells are projected in southern regions and the Northwest (Ch. 2: Our Changing Climate, Figure 2.13) as a result of projected large-scale changes in circulation patterns.

Regional or seasonal water constraints, particularly in the Southwest and Southeast, will result from chronic or seasonal drought, growing populations, and increasing demand for water for various uses (Ch. 2: Our Changing Climate; Ch. 10: Energy, Water, and Land).[29,32] Reduced availability of water for cooling, for hydropower, or for absorbing warm water discharges into water bodies without exceeding temperature limits, will continue to constrain power production at existing facilities and permitting of new power plants. Increases in water temperatures may reduce the efficiency of thermal power plant cooling technologies, potentially leading to warmer water discharge from some power plants, which in turn can affect aquatic life. Studies conducted during 2012 indicate that there is an increasing likelihood of water shortages limiting power plant electricity production in many regions.[21,33]

Hydropower plants in the western United States depend on the seasonal cycle of snowmelt to provide steady output throughout the year. Expected reductions in snowpack in parts of the western U.S. will reduce hydropower production. There will also be increases in energy (primarily electricity) demand in order to pump water for irrigated agriculture and to pump and treat water for municipal uses.[21]

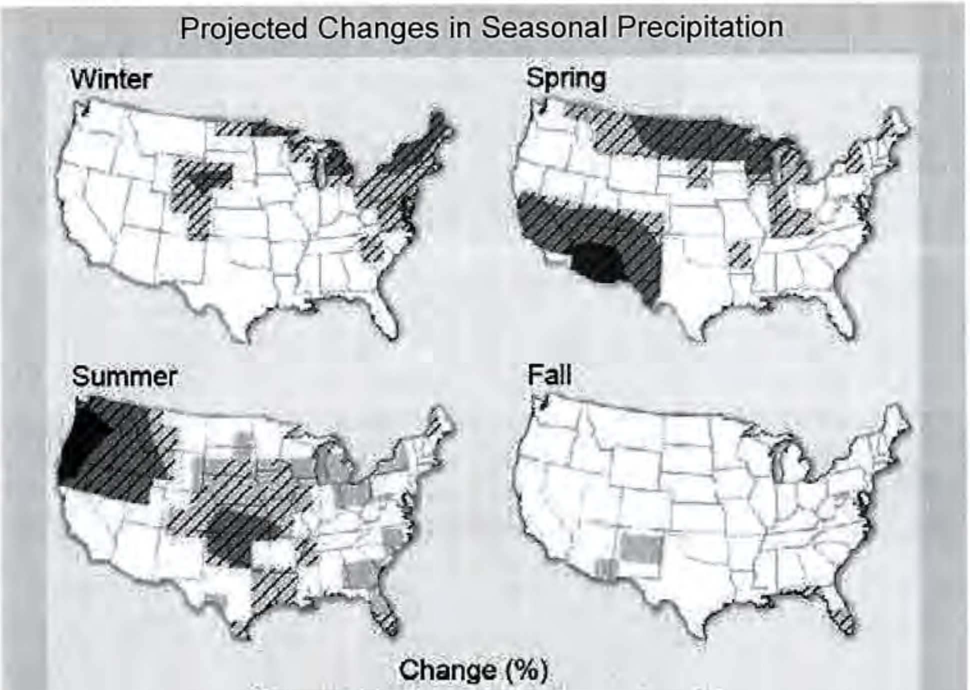


Figure 4.4. Climate change affects precipitation patterns as well as temperature patterns. The maps show projected changes in average precipitation by season for 2041–2070 compared to 1971–1999, assuming emissions of heat-trapping gases continue to rise (A2 scenario). Note significantly drier conditions in the Southwest in spring and Northwest in summer, as well as significantly more precipitation (some of which could fall as snow) projected for northern areas in winter and spring. Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. (Figure source: NOAA NCDC / CICS-NC).

The Electric Power Research Institute's (EPRI) scenario-based technical projections of water demand in 2030 find that one-quarter of existing power generation facilities (about 240,000 megawatts) nationwide are in counties that face some type of water sustainability issue.[34] Many regions face water sustainability concerns, with the most significant water-related stresses in the Southeast, Southwest, and Great Plains regions (Ch. 3: Water).[34]

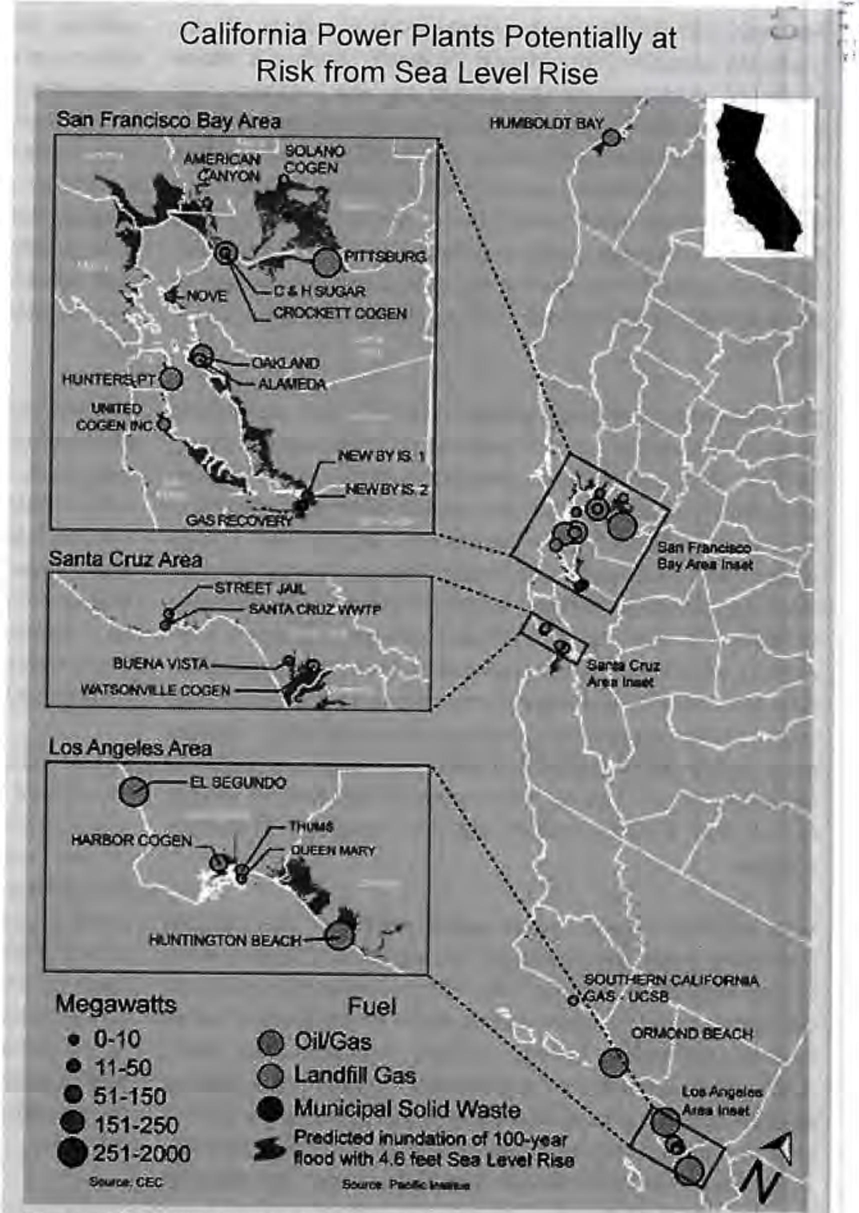
Key Message 4: Sea Level Rise and Infrastructure Damage

In the longer term, sea level rise, extreme storm surge events, and high tides will affect coastal facilities and infrastructure on which many energy systems, markets, and consumers depend.

Significant portions of the nation's energy production and delivery infrastructure are in low-lying coastal areas; these facilities include oil and natural gas production and delivery facilities, refineries, power plants, and transmission lines.

Global sea level has risen by about 8 inches since reliable record keeping began in 1880, affecting countries throughout the world, including the United States. The rate of rise increased in recent decades and is not expected to slow. Global average sea level is projected to rise 1 to 4 feet by 2100 and is expected to continue to rise well beyond this century (Ch. 2: Our Changing Climate). Sea level change at any particular location can deviate substantially from this global average (Ch. 2: Our Changing Climate).[35]

Rising sea levels, combined with normal and potentially more intense coastal storms, an increase in very heavy precipitation events, and local land subsidence, threaten coastal energy equipment as a result of inundation, flooding, and erosion. This can be compounded in areas that are projected to receive more precipitation. In particular, sea level rise and coastal storms pose a danger to the dense network of Outer Continental Shelf marine and coastal facilities in the central Gulf Coast region.[36] Many of California's power plants are at risk from rising sea levels, which result in more extensive coastal storm flooding, especially in the low-lying San Francisco Bay area (Figure 4.5). Power plants and energy infrastructure in coastal areas throughout the United States face similar risks.



California Power Plants Potentially at Risk from Sea Level Rise

Figure 4.5. Rising sea levels will combine with storm surges and high tides to threaten power-generating facilities located in California coastal communities and around the San Francisco Bay. Sea level rise and more intense heavy precipitation events increase the risk of coastal flooding and damages to infrastructure (Ch. 3: Water). (Figure source: Sathaye et al. 2011[37]).

Key Message 5: Future Energy Systems

As new investments in energy technologies occur, future energy systems will differ from today's in uncertain ways. Depending on the character of changes in the energy mix, climate change will introduce new risks as well as opportunities.

Countless aspects of the U.S. economy today are supported by reliable, affordable, and accessible energy supplies. Electricity and other forms of energy are necessary for telecommunications, water and sewer systems, banking, public safety, and more. Today's energy systems vary significantly by region, however, with differences in climate-related impacts also introducing considerable variation by locale. Table 4.3 shows projected impacts of climate change on, and potential risks to, energy systems as they currently exist in different regions. Most vulnerabilities and risks for energy supply and use are unique to local situations, but others are national in scope. For example, biofuels production in three regions (Midwest, Great Plains, and Southwest) could be affected by the projected decrease in precipitation during the critical growing season in the summer months (Ch. 10: Energy, Water, and Land; Ch. 7: Forests).

One certainty about future energy systems is that they will be different than today's, but in ways not yet known. Many uncertainties – financial, economic, regulatory, technological, and so on – will affect private and public consumption and investment decisions on energy fuels, infrastructure, and systems. Energy systems will evolve over time, depending upon myriad choices made by countless decision-makers responding to changing conditions in markets, technologies, policies, consumer preferences, and climate. A key challenge to understanding the nature and intensity of climate change impacts on future energy systems is the amount of uncertainty regarding future choices about energy technologies and their deployment. An evolving energy system is also an opportunity to develop an energy system that is more resilient and less vulnerable to climate change.

Very different future energy supply portfolios are possible depending upon key economic assumptions, including what climate legislation may look like,[14,25,34] and whether significant changes in consumption patterns occur for a variety of other reasons. Renewable energy sources, including solar, wind, hydropower, biofuels, and geothermal are meeting a growing portion of U.S. demand, and there is the opportunity for this contribution to increase in the future (Ch. 6: Agriculture; Ch. 7: Forests). This fundamental uncertainty about the evolving character of energy systems contributes another layer of complexity to understanding how climate change will affect energy systems.

As they consider actions to enhance the resiliency of energy systems, decision-makers confront issues with current energy systems as well as possible future configurations. The systems will evolve and will be more resilient over time if actions tied to features of today's systems do not make future systems less resilient as a result. For example, if moving toward biomass as an energy source involves more water-consumptive energy supplies that could be constrained by drier future climate conditions, then decisions about energy choices should be made with consideration of potential changes in climate conditions and the risks these changes present (See Ch. 26: Decision Support).

Because energy systems in the United States are not centrally planned, they tend to reflect energy decisions shaped by law, regulation, other policies, and economic, technological, and other factors in markets. Trends in use patterns may continue into the future; this is an opportunity to increase resilience but also a major uncertainty for energy utilities and policy makers. Energy infrastructure tends to be long-lived, so resiliency can be enhanced by more deliberate applications of risk-management techniques and information about anticipated climate impacts and trends.[38]

For example, risk-management approaches informed by evolving climate conditions could be used to project the value of research and development on, or investments in, construction of dikes and barriers for coastal facilities or for dry-cooling technologies for power plants in regions where water is already in short supply. Solar and wind electricity generation facilities could be sited in areas that are initially more expensive (such as offshore areas) but less subject to large reductions in power plant output resulting from climatic changes. Targets for installed reserve margins for electric generating capacity and capacity of power lines can be established using certain temperature expectations, but adjusted as conditions unfold over time.

A range of climate change impacts will affect future energy production. This table shows possible ways to anticipate and respond to these changes. Innovations in technologies may provide additional opportunities and benefits to these and other adaptation actions. Behavioral change by consumers can also promote resiliency.

Table 4.2 summarizes actions that can be taken to increase the ease with which energy systems can adjust to climate change. Many of these adaptation investments entail "no regrets" actions, providing short-term benefits because they address current vulnerabilities as well as future risks.

Possible Climate Resilience and Adaptation Actions in Energy Sector

	Key Challenges Addressed			
Possible Actions	**Extreme Weather Events**	**Increase in Peak Energy Loads**	**Water Constraints on Energy Production**	**Sea Level Rise**
Supply: System and Operational Planning				
Diversifying supply chains	X	X	X	X
Strengthening and coordinating emergency response plans	X	X	X	
Providing remote/protected emergency-response coordination centers	X			
Developing flood-management plans or improving stormwater management	X			X
Developing drought-management plans for reduced cooling flows			X	
Developing hydropower management plans/policies addressing extremes			X	
Supply: Existing Equipment Modifications				
Hardening/building redundancy into facilities	X	X		
Elevating water-sensitive equipment or redesigning elevation of intake structures	X			X
Building coastal barriers, dikes, or levees	X			X
Improving reliability of grid systems through back-up power supply, intelligent controls, and distributed generation	X	X	X	
Insulating equipment for temperature extremes	X			
References to technical studies with case studies on many of these topics may be found in Wilbanks et al. 2012.[4]				
Implementing dry (air-cooled) or low-water hybrid (or recirculating) cooling systems for power plants			X	
Adding technologies/systems to pre-cool water discharges			X	
Using non-fresh water supplies: municipal effluent, brackish or seawater			X	
Relocating vulnerable facilities	X		X	X
Supply: New Equipment				
Adding peak generation, power storage capacity, and distributed generation	X	X	X	X
Adding back-up power supply for grid interruptions	X	X	X	
Increasing transmission capacity within and between regions	X	X	X	X
Use: Reduce Energy Demand				
Improving building energy, cooling-system and manufacturing efficiencies, and demand-response capabilities (for example, smart grid)	X	X		
Setting higher ambient temperatures in buildings	X	X		
Improving irrigation and water distribution/reuse efficiency		X	X	
Allowing flexible work schedules to transfer energy use to off-peak hours		X		

Table 4.3. Increased temperatures, changing precipitation patterns, and sea level rise will affect many sectors and regions, including energy production, agriculture yields, and infrastructure damage. Changes are also projected to affect hydropower, solar photovoltaic, and wind power, but the projected impacts are not well defined at this time.

Energy Supply: Summary of National and Regional Impacts, Challenges, and Opportunities							
Consequences[a]: Challenges and Opportunities							
	Fuel Extraction, Production and Refining		Fuel Distribution Transport/ Pipelines	Electricity Generation			Electricity Distribution
	Hydrocarbons[b]	Biofuels		Thermal Power Generation[c]			
Physical Impacts – High Likelihood	Increased Ambient Temperature of Air and Water	Increased Extremes in Water Availability	Coastal Erosion and Sea Level Rise	Increased Ambient Temperature of Air and Water	Increased Extremes in Water Availability	Coastal Erosion and Sea Level Rise	Hot Summer Periods
National Trend Summary[f] Consequence	Decreased Production and Refining Capacity	Decreased Agricultural Yields	Damage to Facilities	Reduced Plant Efficiency and Cooling Capacity	Interruptions to Cooling Systems	Damage to Facilities	Reduced Capacity/Damage to Lines
Key Indicator (2071-2099 vs. 1971-2000)	**Mean Annual Temperature[d]**	**Summer Precipitation[d]**	**Sea level Rise[e] (2100)**	**Mean Annual Temperature[d]**	**Summer Precipitation[d]**	**Sea Level Rise[e] (2100)**	**# Days>90°F[f,g] (2055)**
Northeast	+4°F to 9°F	-5% to +6%	1.6–3.9 ft (0.5–1.2m)	+4°F to 9°F	-5% to +6%	1.6–3.9 ft. (0.5–1.2m)	+13 days
Southeast	+3°F to 8°F	-22% to +10%		+3°F to 8°F	-22% to +10%		+31 days
Midwest	+4°F to 10°F	-22% to +7%		+4°F to 10°F	-22% to +7%		+19 days
Great Plains	+3°F to 9°F	-27% to +5%		+3°F to 9°F	-27% to +5%		+20 days
Southwest	+4°F to 9°F	-13% to +3%		+4°F to 9°F	-13% to +3%		+24 days
Northwest	+3°F to 8°F	-34% to -4%		+3°F to 8°F	-34% to -4%		+4 days
Alaska	+4°F to 9°F	+10% to +25%		+4°F to 9°F	+10% to +25%		No Projection
Pacific Islands	+2°F to 5°F	Range from little change to increases		+2°F to 5°F	Range from little change to increases		No Projection

Notes

a) Excludes extreme weather events.

b) Hydrocarbons include coal, oil, and gas including shales.

c) Thermal power generation includes power plants fired from nuclear, coal, gas, oil, biomass fuels, solar thermal, and geothermal energy.

d) CMIP3 15 GCM Models: 2070–2099 Combined Interquartile Ranges of SRES B1 and A2 (versus 1971–2000), incorporating uncertainties from both differences in model climate sensitivity and differences between B1 and A2 in emissions trajectories

e) Range of sea level rise for 2100 is the Low Intermediate to High Intermediate Scenario from "Sea Level Change Scenarios for the U.S. National Climate Assessment."[35] Range is similar to the 1 to 4 feet of sea level rise projected in Ch. 2: Our Changing Climate, Key Message 10. There will be regional variations in sea level rise, and this category of impacts does not apply for the Midwest region.

f) 2055 NARCCAP

g) References:[4,25]

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4: ENERGY SUPPLY AND USE

SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages:

The author team met bi-weekly by teleconference during the months of March through July 2012. Early in the development of key messages and a chapter outline, the authors reviewed all of the four dozen relevant technical input reports that were received in response to the Federal Register solicitation for public input. Selected authors participated in a U.S. Department of Energy (DOE) sponsored workshop on Energy Supply and Use, December 29-30, 2011, in Washington, D.C. The workshop was organized specifically to inform a DOE technical input report and this National Climate Assessment and to engage stakeholders in this process. The authors selected key messages based on the risk and likelihood of impacts, associated consequences, and available evidence. Relevance to decision support within the energy sector was also an important criterion.

The U.S. maintains extensive data on energy supply and use. The Energy Information Administration (EIA) of the U.S. Department of Energy is a primary organization in this activity, and data with quality control, quality assurance, and expert review are available through EIA Web pages (for example, EIA 2012, EIA 2013[39]).

KEY MESSAGE #1 TRACEABLE ACCOUNT

Extreme weather events are affecting energy production and delivery facilities, causing supply disruptions of varying lengths and magnitudes and affecting other infrastructure that depends on energy supply. The frequency and intensity of certain types of extreme weather events are expected to change.

Description of evidence base

A series of NCA workshops reviewed potential influences of climate change thus far on the frequency and intensity of certain types of extreme events.[3] Numerous past extreme events demonstrate damage to energy facilities and infrastructure. Data assembled and reviewed by the Federal Government summarize typical costs associated with damage to energy facilities by extreme events.[5] State and regional reports as well as data provided by public utilities document specific examples.[4,9,10,26]

Damage to Gulf Coast energy facilities and infrastructure by Hurricanes Katrina and Rita in 2005 provides excellent examples to support this key message.[8,9] Wildfire also damages transmission grids.[10]

The authors benefited from Agency-sponsored technical input reports summarizing relevant data and information on energy supply and use as well as urban systems and infrastructure.[4,21,25] A number of other technical input reports were relevant as well. These were reviewed carefully, particularly with regard to the identification of key messages.

New information and remaining uncertainties

The information provided through a series of NCA workshops provided new (and current) evidence for influences of climate change on the frequency and intensity of extreme events. The summaries from those workshops provide succinct evidence that certain extreme events that damage energy facilities and infrastructure can be expected to increase in number and intensity with climate change (for example, Peterson et al. 2012[3]). Documentation of damage to energy facilities and infrastructure continues to accumulate, increasing confidence in this key message.[5,14]

The regional and local character of extreme events varies substantially, and this variability is a source of significant uncertainty regarding the impacts of climate change and consequences in terms of damage to energy facilities by extreme events. Additionally, damage to energy infrastructure in a specific location can have far-reaching consequences for energy production and distribution, and synthesis of such indirect consequences for production and distribution does not yet support detailed projections.

Assessment of confidence based on evidence

High. There is high consensus with moderate evidence that extreme weather events associated with climate change will increase disruptions of energy infrastructure and services in some locations.

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

Higher summer temperatures will increase electricity use, causing higher summer peak loads, while warmer winters will decrease energy demands for heating. Net electricity use is projected to increase.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the energy supply and use technical input.[4] Global climate models simulate increases in summer temperatures, and the NCA climate scenarios[2,20] describe this aspect of climate change projections for use in preparing this report (Ch. 2: Our Changing Climate). Data used by Kunkel et al.[2] and Census Bureau population data, synthesized by the EIA,[15] were the basis for calculating population-weighted heating and cooling degree-days over the historic period as well as projections assuming SRES B1 and A2 scenarios.

The NCA climate scenarios[2] project an increase in the number of cooling days and decrease in heating days, with peak electricity demand in some regions shifting from winter to summer[27] and shifting to electricity needs for cooling instead of fossil fuels for heating.[25,26,27]

New information and remaining uncertainties

While there is little uncertainty that peak electricity demands will increase with warming by climate change, substantial regional variability is expected. Climate change projections do not provide sufficient spatial and temporal detail to fully analyze these consequences. Socioeconomic factors including population changes, economic conditions, and energy prices, as well as technological developments in electricity generation and industrial equipment, will have a strong bearing on electricity demands, specific to each region of the country.

Assessment of confidence based on evidence

High. Assuming specific climate change scenarios, the consequences for heating and cooling buildings are reasonably predictable, especially for the residential sector. With a shift to higher summer demands for electricity, peak demands for electricity can be confidently expected to increase.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Changes in water availability, both episodic and long-lasting, will constrain different forms of energy production.

Description of evidence base

Climate scenarios prepared for the NCA[2] describe decreases in precipitation under the SRES A2 scenario, with the largest decreases across the Northwest and Southwest in the spring and summer.

Technical input reports (for example, Wilbanks et al.[4,21]) summarize data and studies show that changes in water availability will affect energy production,[33] and more specifically, that water shortages will constrain electricity production (Ch. 2: Our Changing Climate).[29,32] The impacts of drought in Texas during 2011 are an example of the consequences of water shortages for energy production as well as other uses (Ch. 10: Energy, Water, and Land). Electric utility industry reports document potential consequences for operation of generating facilities.[34] A number of power plants across the country have experienced interruptions due to water shortages.

New information and remaining uncertainties

An increasing number of documented incidents of interruptions in energy production due to water shortages provide strong evidence that decreased precipitation or drought will have consequences for energy production.[21]

There is little uncertainty that water shortages due to climate change will affect energy production. But uncertainty about changes in precipitation and moisture regimes simulated by global climate models is significantly higher than for simulated warming. Additionally, climate change simulations lack the spatial and temporal detail required to analyze the consequences for water availability at finer scales (for example, local and regional). Finer-scale projections would be relevant to decisions about changes in energy facilities to reduce risk or adapt to water shortages associated with climate change.

Assessment of confidence based on evidence

High. The evidence is compelling that insufficient water availability with climate change will affect energy production; however, simulations of climate change lack the detail needed to provide more specific information for decision support.

KEY MESSAGE #4 TRACEABLE ACCOUNT

In the longer term, sea level rise, extreme storm surge events, and high tides will affect coastal facilities and infrastructure on which many energy systems, markets, and consumers depend.

Description of evidence base

The sea level change scenario report prepared for the NCA (see also Ch. 2: Our Changing Climate)[35] provides further information about sea level change. Extreme surge events at high tides are expected to increase,[11] raising the risk of inundating energy facilities such as power plants, refineries, pipelines, and transmission and distribution networks (for example, Sathaye et al. 2013[10]) Data available through the EIA (for example, EIA 2010[15] provide high-quality information about the locations and distribution of energy facilities.

A substantial portion of the nation's energy facilities and infrastructure are located along coasts or offshore, and sea level rise will affect these facilities (Ch. 25: Coasts; Ch. 17: Southeast; Ch. 5: Transportation).[4,10,21,36]

New information and remaining uncertainties

Projections of sea level change are relatively uncertain compared to other aspects of climate change. More importantly, there will be substantial regional and local variability in sea level change, and facilities in locations exposed to more frequent and intense extreme wind and precipitation events will be at higher risk. Data and analyses to understand regional and local sea level change are improving, but substantial uncertainty remains and decision support for adaptation is challenged by these limitations.

Assessment of confidence based on evidence

High. There is high confidence that increases in global mean sea level, extreme surge events, and high tides will affect coastal energy facilities; however, regional and local details are less certain.

KEY MESSAGE #5 TRACEABLE ACCOUNT

As new investments in energy technologies occur, future energy systems will differ from today's in uncertain ways. Depending on the character of changes in the energy mix, climate change will introduce new risks as well as opportunities.

Description of evidence base

A number of studies describe U.S. energy system configurations in terms of supply and use assuming different scenarios of climate change, including SRES B1 and A2.[14,25,34] A technical input report to the NCA by DOE[4,21] provides details and updates earlier studies. The potential role of biofuels is described within chapters 6 and 7 of this report (Ch. 6: Agriculture; Ch. 7: Forests).

New information and remaining uncertainties

Understanding of options for future energy supply and use within the U.S. improves, as the EIA and other organizations update data and information about U.S. energy systems as well as projections of the mix of primary energy under various assumptions about demographic, economic, and other factors. With additional data and better models, alternative energy mixes can be explored with respect to climate change adaptation and mitigation. But numerous factors that are very difficult to predict – financial, economic, regulatory, technological – affect the deployment of actual facilities and infrastructure.

Assessment of confidence based on evidence

High. Given the evidence about climate change impacts and remaining uncertainties associated with the future configuration of energy systems and infrastructure, there is high confidence that U.S. energy systems will evolve in ways that affect risk with respect to climate change and options for adaptation or mitigation.

Climate Change Impacts in the United States

CHAPTER 5
TRANSPORTATION

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5 TRANSPORTATION

KEY MESSAGES

1. **The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are affecting the reliability and capacity of the U.S. transportation system in many ways.**
2. **Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts on transportation infrastructure, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.**
3. **Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.**
4. **Climate change impacts will increase the total costs to the nation's transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.**

The U.S. economy depends on the personal and freight mobility provided by the country's transportation system. Essential products and services like energy, food, manufacturing, and trade all depend in interrelated ways on the reliable functioning of these transportation components. Disruptions to transportation systems, therefore, can cause large economic and personal losses.[1] The national transportation system is composed of four main components that are increasingly vulnerable to climate change impacts:

- fixed node infrastructure, such as ports, airports, and rail terminals;
- fixed route infrastructure, such as roads, bridges, pedestrian/bicycle trails and lanes, locks, canals/channels, light rail, subways, freight and commuter railways, and pipelines, with mixed public and private ownership and management;
- vehicles, such as cars, transit buses, and trucks; transit and railcars and locomotives; ships and barges; and aircraft – many privately owned; and
- the people, institutions, laws, policies, and information systems that convert infrastructure and vehicles into working transportation networks.

Besides being affected by climate changes, transportation systems also contribute to changes in the climate through emissions. In 2010, the U.S. transportation sector accounted for 27% of total U.S. greenhouse gas emissions, with cars and trucks accounting for 65% of that total.[2] Petroleum accounts for 93% of the nation's transportation energy use.[2] This means that policies and behavioral changes aimed at reducing greenhouse gas emissions will have significant implications for the various components of the transportation sector.

Weather events influence the daily and seasonal operation of transport systems.[3,4,5] Transportation systems are already experiencing costly climate change related impacts. Many inland states – for example, Vermont, Tennessee, Iowa, and Missouri – have experienced severe precipitation events, hail, and flooding during the past three years, damaging roads, bridges, and rail systems and the vehicles that use them. Over the coming decades, all regions and modes of transportation will be affected by increasing temperatures, more extreme weather events, and changes in precipitation. Concentrated transportation impacts are likely in Alaska and along seacoasts.


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Climate trends affect the design of transport infrastructure, which is expensive and designed for long life (typically 50 to 100 years). The estimated value of U.S. transportation facilities in 2010 was $4.1 trillion.[6] As climatic conditions shift, portions of this infrastructure will increasingly be subject to climatic stresses that will reduce the reliability and capacity of transportation systems.[7] Transportation systems are also vulnerable to interruptions in fuel and electricity supply, as well as communications disruptions – which are also subject to climatic stresses.[7,8] For example, power outages resulting from Hurricane Katrina shut down three major petroleum pipelines for two days, and the systems operated at reduced capacities for two weeks.[9]

Climate change will affect transportation systems directly, through infrastructure damage, and indirectly, through changes in trade flows, agriculture, energy use, and settlement patterns. If, for instance, corn cultivation shifts northward in response to rising temperatures, U.S. agricultural products may flow to markets from different origins by different routes.[10] If policy measures and technological changes reduce greenhouse gas emissions by affecting fuel types, there will likely be significant impacts on the transportation of energy supplies (such as pipelines and coal trains) and on the cost of transportation to freight and passenger users.[11]

Shifts in demographic trends, land-use patterns, and advances in transportation technology over the next few decades will have profound impacts on how the nation's transportation system functions, its design, and its spatial extent. As transportation officials shape the future transportation system to address new demands, future climate conditions should be considered as part of the planning and decision-making process.

Disruptions to transportation system capacity and reliability can be partially offset by adaptations. Transportation systems *as networks* may use alternative routes around damaged elements or shift traffic to undamaged modes. Other adaptation actions include new infrastructure designs for future climate conditions, asset management programs, at-risk asset protection, operational changes, and abandoning/relocating infrastructure assets that would be too expensive to protect.[12] As new and rehabilitated transportation systems are developed, climate change impacts should be routinely incorporated into the planning for these systems.

There will be challenges in adapting transportation systems to climate related changes, particularly when factoring in projected growth in the transportation sector. A National Surface Transportation Policy and Revenue Commission in 2007 forecast the following annual average growth rates: average annual tonnage growth rates of 2.1% for trucks, 1.9% for rail, and 1.2% for waterborne transportation, and an average annual passenger vehicle miles traveled growth rate of 1.82% through 2035 and 1.72% through 2055.[13]

Key Message 1: Reliability and Capacity at Risk

The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are affecting the reliability and capacity of the U.S. transportation system in many ways.

Global climate change has both gradual and extreme event implications. A gradually warming climate will accelerate asphalt deterioration and cause buckling of pavements and rail lines.[14] Streamflows based on increasingly more frequent and intense rainfall instead of slower snowmelt could increase the likelihood of bridge damage from faster-flowing streams.[15] However, less snow in some areas will reduce snow removal costs and extend construction seasons. Shifts in agricultural production patterns will necessitate changes in transportation routes and modes.[16]

Climate models project that extreme heat and heat waves will become more intense, longer lasting, and more frequent (Ch. 2: Our Changing Climate). By 2080-2100, average temperatures are expected to increase by 3°F to 6°F for the continental United States, assuming emissions reductions from current trends (B1 scenario), while continued increases in emissions (A2 scenario) would lead to an increase in average temperatures ranging from 5°F in Florida to 9°F in the upper Midwest.[17]

The impact on transportation systems not designed for such extreme temperatures would be severe. At higher temperatures, expansion joints on bridges and highways are stressed and some asphalt pavements deteriorate more rapidly.[18] Rail

THAWING ALASKA

Permafrost – soil saturated with frozen water – is a key feature of the Alaskan landscape. *Frozen* permafrost is a suitable base for transportation infrastructure such as roads and airfields. In rapidly warming Alaska, however, as permafrost thaws into mud, road shoulders slump, highway cuts slide, and runways sink. Alaska currently spends an extra $10 million per year repairing permafrost damage.[25]

A recent study, which examined potential climate damage to Alaskan public infrastructure using results from three different climate models,[26] considered 253 airports, 853 bridges, 131 harbors, 819 miles of railroad, 4,576 miles of paved road, and 5,000 miles of unpaved road that could be affected by climate change. The present value of additional public infrastructure costs due to climate change impacts was estimated at $5.6 to $7.6 billion through 2080, or 10% to 12% of total public infrastructure costs in Alaska. These costs might be reduced by 40% with strong adaptation actions.[26]

track stresses and track buckling will increase.[14,19] High air temperatures can affect aircraft performance; lift-off limits at hot-weather and high-altitude airports will reduce aircraft operations.[20]

Construction crews may have to operate on altered time schedules to avoid the heat of the day, with greater safety risks for workers.[21] The construction season may lengthen in many localities. Similarly, higher temperatures (and precipitation changes) are likely to affect transit ridership, bicycling, and walking.[14,22]

Climate change is most pronounced at high northern latitudes. Alaska has experienced a 3°F rise in average temperatures since 1949,[23] double the rest of the country. Winter temperatures have risen by 6°F.[23] On the North Slope, sea ice formerly provided protection to the shoreline against strong fall/winter winds and storms (see Ch. 12: Indigenous Peoples). Retreating ice reduces this protection, eroding the shoreline and endangering coastal villages. Thawing permafrost is causing pavement, runway, rail, and pipeline displacements, creating problems for operation and maintenance, and requiring reconstruction of key facilities.

Arctic warming is also projected to allow the seasonal opening of the Northwest Passage to freight shipment.[24] Global climate projections to 2100 show extensive open water areas during the summer around the Arctic basin. Retreat of Arctic sea ice has been observed in all seasons over the past five decades, with the most prominent retreat in summer.[24] This has allowed a limited number of freighters, cruise ships, and smaller vessels to traverse the Northwest Passage for several years.

Possible Future Flood Depths in Mobile, AL with Rising Sea Level

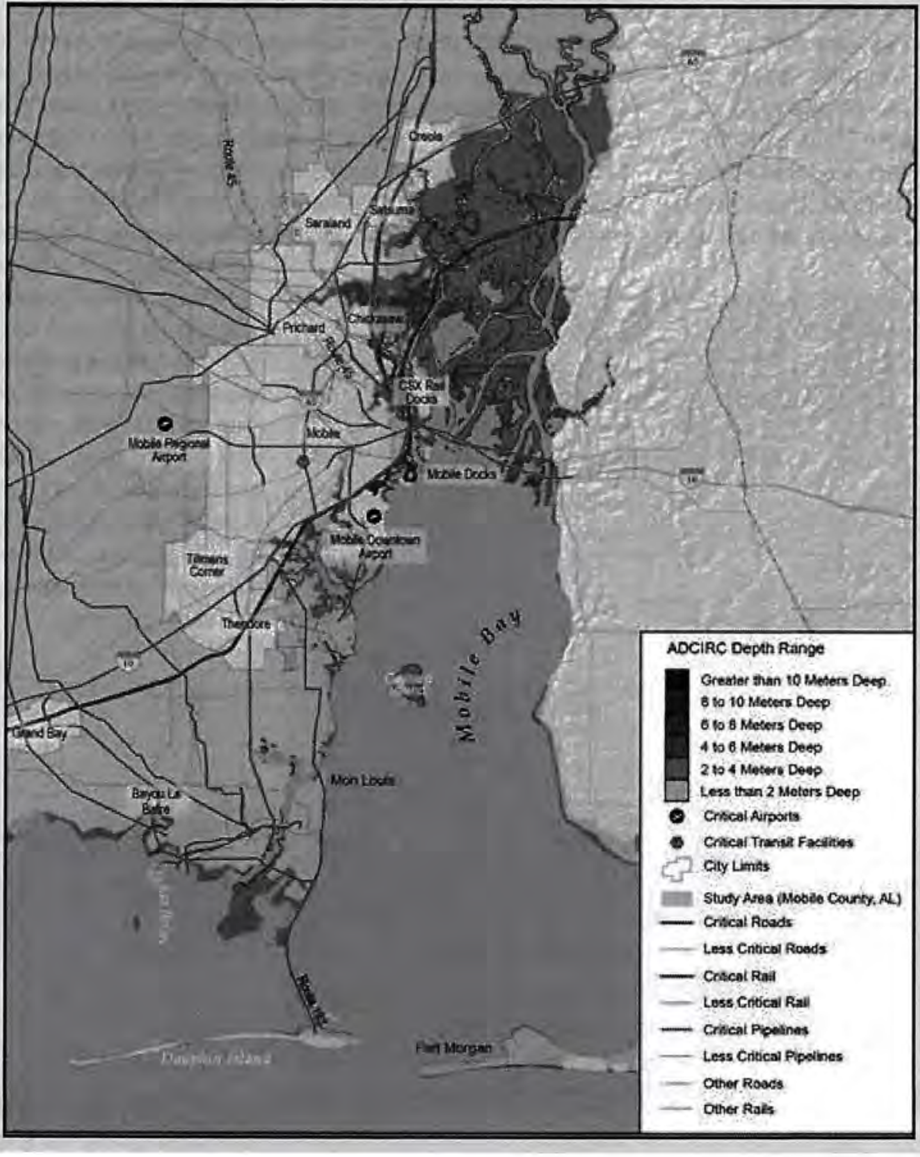

Figure 5.1. Many coastal areas in the United States, including the Gulf Coast, are especially vulnerable to sea level rise impacts on transportation systems.[11,27,28] This is particularly true when one considers the interaction among sea level rise, wave action, and local geology.[29] This map shows that many parts of Mobile, Alabama, including critical roads, rail lines, and pipelines, would be exposed to storm surge under a scenario of a 30-inch sea level rise combined with a storm similar to Hurricane Katrina. Not all roads would be flooded if they merely run through low areas since some are built above flood levels. A 30-inch sea level rise scenario is within the range projected for global sea level rise (Ch. 2: Our Changing Climate, Key Message 10). (Figure source: U.S. Department of Transportation 2012[30]).

Key Message 2: Coastal Impacts

Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts on transportation infrastructure, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.

The transportation impacts of rising global sea level, which is expected to continue to rise by an additional 1 to 4 feet by 2100 (see also Ch. 2: Our Changing Climate, Key Message 10),[31] will vary widely by location and geography. When sea level rise is coupled with intense storms, the resulting storm surges will be greater, extend farther inland, and cause more extensive damage. Relative sea level rise will be greater along some coasts (such as Louisiana, Texas, and parts of the Chesapeake Bay), and this will have significant effects on transportation infrastructure, even without the coupling with storms, due to regional land subsidence (land sinking or settling) (Ch. 25: Coasts). Ports and harbors will need to be reconfigured to accommodate higher seas. Many of the nation's largest ports are along the Gulf Coast, which is especially vulnerable due to a combination of sea level rise, storm surges, erosion, and land subsidence.[11] Two additional impacts for ports include 1) as sea level rises, bridge clearance may not be adequate to allow safe passage of large vessels; 2) even if the elevation of port facilities is adequate, any main access road that is not elevated will become more frequently inundated, thus affecting port operations. In 2011, the United States imported 45% of all oil consumed, and 56% of those imports passed through Gulf Coast ports.[32]

More frequent disruptions and damage to roads, tracks, runways, and navigation channels are projected in coastal areas beyond the Gulf Coast. Thirteen of the nation's 47 largest airports have at least one runway with an elevation within 12 feet of current sea levels.[33] Most ocean-going ports are in low-lying coastal areas, including three of the most important for imports and exports: Los Angeles/Long Beach (which handles 31% of the U.S. port container movements) and the Port of South Louisiana and the Port of Galveston/Houston (which combined handle 25% of the tonnage handled by U.S. ports).[34] Extreme floods and storms associated with climate change will lead to increased movement of sediment and buildup of sandy formations in channels. For example, many federally maintained navigation channels have deteriorated in recent years to dimensions less than those authorized, in part due to floods and storms, which resulted in reduced levels of service that affect navigation safety and reliability.[35] Channels that are not well maintained and have less sedimentation storage volume will thus be more vulnerable to significant, abrupt losses in navigation service levels. Additional channel storage capacity that may be created by sea level rise will also increase water depths and increase sedimentation in some channels. (See Ch. 25: Coasts for additional discussion of coastal transportation impacts.)

Figure 5.2. Thirteen of the nation's 47 largest airports have at least one runway with an elevation within the reach of moderate to high storm surge. Sea level rise will pose a threat to low-lying infrastructure, such as the airports shown here. (Data from Federal Aviation Administration 2012[33]).

Key Message 3: Weather Disruptions

Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.

Changes in precipitation patterns, particularly more extreme precipitation events and drought, will affect transportation systems across the country. Delays caused by severe storms disrupt almost all types of transportation. Storm drainage systems for highways, tunnels, airports, and city streets could prove inadequate, resulting in localized flooding. Bridge piers are subject to scour as runoff increases stream and river flows, potentially weakening bridge foundations. Severe storms will disrupt highway traffic, leading to more accidents and delays. More airline traffic will be delayed or canceled.


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Infrastructure around the country has been compromised by extreme weather events such as heavy downpours. Road and bridge damage are among the infrastructure failures that have occurred during these extreme events.

Inland waterways may well experience greater floods, with high flow velocities that are unsafe for navigation and that cause channels to shut down intermittently. Numerous studies indicate increasing severity and frequency of flooding throughout much of the Mississippi and Missouri River Basins.[36] Increases in flood risk reflect both changing precipitation and changing land-use patterns.[37] In the Upper Mississippi/Missouri Rivers, there have been two 300- to 500-year floods over the past 20 years.[38] Drought increases the probability of wildfires, which affect visibility severely enough to close roads and airports. Drought can lower vessel drafts on navigable rivers and associated lock and dam pools. On the other hand, less ice formation on navigable waterways has the potential to increase seasonal windows for passage of navigation.

Gulf Coast Transportation Hubs at Risk

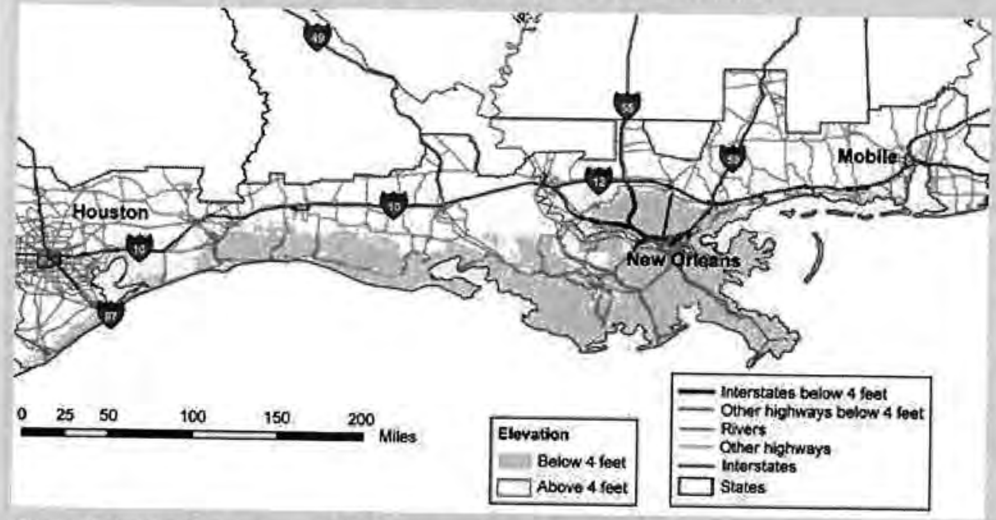

Figure 5.3. Within this century, 2,400 miles of major roadway are projected to be inundated by sea level rise in the Gulf Coast region. The map shows roadways at risk in the event of a sea level rise of about 4 feet, which is within the range of projections for this region in this century (see also Ch. 2: Our Changing Climate, Key Message 10). In total, 24% of interstate highway miles and 28% of secondary road miles in the Gulf Coast region are at elevations below 4 feet. (Figure source: Kafalenos et al. 2008[39]).

The frequency of the strongest hurricanes (Category 4 and 5) in the Atlantic is expected to increase (see Ch. 2: Our Changing Climate, Key Message 8). As hurricanes approach landfall, they create storm surge, which carries water farther inland. The resulting flooding, wind damage, and bridge destruction disrupts virtually all transportation systems in the affected area. Many of the nation's military installations are in areas that are vulnerable to extreme weather events, such as naval bases located in hurricane-prone zones.

HURRICANE SANDY

On October 29, 2012, Hurricane Sandy dealt the transportation systems of New Jersey and New York and environs a massive blow (See also Ch.16: Northeast, "Hurricane Vulnerability"; Ch. 11: Urban "Hurricane Sandy"). The damages from Sandy are indicative of what powerful tropical storms and higher sea levels could bring on a more frequent basis in the future and were very much in line with vulnerability assessments conducted over the past four years.[40,41,42] All tunnels and most bridges leading into New York City were closed during the storm. Storm tides of up to 14 feet[43] flooded the Queens Midtown, Holland, and Carey (Brooklyn Battery) tunnels, which remained closed for at least one week (two weeks for the Carey Tunnel) while floodwaters were being pumped out and power restored. The three major airports (Kennedy, Newark, and LaGuardia) flooded, with LaGuardia absorbing the worst impact and closing for three days.[44]

Hurricane Sandy Causes Flooding in New York City Subway Stations

Figure 5.4. The nation's busiest subway system sustained the worst damage in its 108 years of operation on October 29, 2012, as a result of Hurricane Sandy. Millions of people were left without service for at least one week after the storm, as the Metropolitan Transportation Authority rapidly worked to repair extensive flood damage (Photo credit: William Vantuono, Railway Age Magazine, 2012[46]).

Almost 7.5 million passengers per day ride the New York City subways and buses.[45] Much of the New York City subway system below 34th Street was flooded, including all seven tunnels under the East River to Brooklyn and Queens. In addition to removing the floodwaters, all electrical signaling and power systems (the third rails) had to be cleaned, inspected, and repaired. Service on most Lower Manhattan subways was suspended for at least one week,[46] as was the PATH system to New Jersey.[47] Commuter rail service to New Jersey, Long Island, and northern suburbs, with more than 500,000 passengers per day,[45] was similarly affected for days or weeks with flooded tunnels, downed trees and large debris on tracks, and loss of electrical power.[48] In addition, miles of local roads, streets, underpasses, parking garages, and bridges flooded and/or were badly damaged in the region, and an estimated 230,000 parked vehicles[49] sustained water damage. Flooded roadways prevented the New York Fire Department from responding to a fire that destroyed more than 100 homes in Brooklyn's Breezy Point neighborhood.[50]

Hurricane Sandy's storm surge produced nearly four feet of floodwaters throughout the Port of New York and New Jersey, damaging electrical systems, highways, rail track, and port cargo; displacing hundreds of shipping containers; and causing ships to run aground.[51] Floating debris, wrecks, and obstructions in the channel had to be cleared before the Port was able to reopen to incoming vessels within a week.[52] Pleasure boats were damaged at marinas throughout the region. On a positive note, the vulnerability analyses prepared by the metropolitan New York authorities and referenced above provided a framework for efforts to control the damage and restore service more rapidly. Noteworthy are the efforts of the Metropolitan Transportation Authority to protect vital electrical systems and restore subway service to much of New York within four days.

The impacts of this extraordinary storm on one of the nation's most important transportation nodes were felt across the country. Airline schedules throughout the United States and internationally were snarled; Amtrak rail service along the East Coast and as far away as Buffalo and Montreal was curtailed; and freight shipments in and out of the hurricane impact zone were delayed. The resultant direct costs to the community and indirect costs to the economy will undoubtedly rise into the tens of billions of dollars (See also Ch. 11: Urban, "Hurricane Sandy").

Table 5.1 relates to overall national expectations based on Angel and Kunkel 2010[54] and as postulated by chapter authors. This kind of matrix is likely to be most valuable and accurate if used at the state/regional/local levels. (Source: Matrix format adapted from McLaughlin et al. 2011[53]).

Illustrative Risks of Climate-related Impacts

Likelihood of Occurrence

Magnitude of Consequences	Low	Medium	High	Virtually Certain
High	Subway and tunnel flooding	Increased widespread flooding of transportation facilities	Major localized flooding disrupts transportation systems	Inundation of coastal assets due to storm surge
Medium	Increased rock/mud slides blocking road and rail facilities	Train derailment due to rail buckling	Increased disruption of barge traffic due to flooding	Short-term road flooding and blocked culverts due to extreme events
Low	Lower visibility from wildfires due to drought conditions	Northward shift of agricultural production places more demand and stress on roads and systems not prepared for higher volumes	Pavement heaving and reduced pavement life due to high temperatures	Inundation of local roads due to sea level rise
Positive (beneficial)	Reduced flight cancellations due to fewer blizzards	Reduced maintenance costs for highways and airports due to warmer winters	Reduced Great Lakes freezing, leading to longer shipping season	Longer seasonal opening of Northwest Passage

Risks and Consequences

Risk is a function of both likelihood of impact and the consequences of that impact. Table 5.1 is an illustrative application of a risk matrix adapted from the Port Authority of New York and New Jersey. As shown, different types of climate-related incidents/events can have associated with them a likelihood of occurrence and a magnitude of the consequences if the incident does occur.

In assessing consequences, the intensity of system use, as well as the existence or lack of alternative routes, must be taken into account. Disabling a transportation facility can have ripple effects across a network, with trunk (main) lines and hubs having the most widespread impacts.[53] Any comprehensive assessment of the consequences of climate change would need to encompass the broad array of factors that influence the nation's transportation system, and consider changes in population, society, technology, prices, regulation, and the economy that eventually affect transportation system performance.[55] For example, the trend in recent years in the U.S. economy of adopting just-in-time logistics increases the vulnerability of businesses to day-to-day disruptions caused by weather and flooding.

Key Message 4: Costs and Adaptation Options

Climate change impacts will increase the total costs to the nation's transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.

Adaptation strategies can be employed to reduce the impact of climate change related events and the resulting consequences (see Ch. 28: Adaptation). Consideration of adaptation strategies in the transportation sector is especially important in the following five areas:

- **Transportation and land-use planning:** deciding what infrastructure to build and where to build it, as well as planning for vulnerable areas of the community and impacts on specific population groups.
- **Vulnerability and risk assessment**: identifying existing vulnerable facilities and systems, together with the expected consequences.
- **New infrastructure design**: adapting new infrastructure designs that anticipate changing environmental and operational conditions.
- **Asset management**: adapting existing infrastructure and operations that respond to current and anticipated conditions, including changed maintenance practices and retrofits.
- **Emergency response:** anticipating expected disruptions from extreme weather events, and developing emergency response capability.

Adaptation takes place at multiple levels, from individual households and private businesses to federal, state, and local governments. The impacts associated with climate change are not new, since flooding, storm surge, and extreme heat have long been challenges. What *is* new is the changing frequency, intensity, and location/geography of impacts and hazards.

Responding effectively to present and future environmental challenges enhances the resilience of communities. Examples

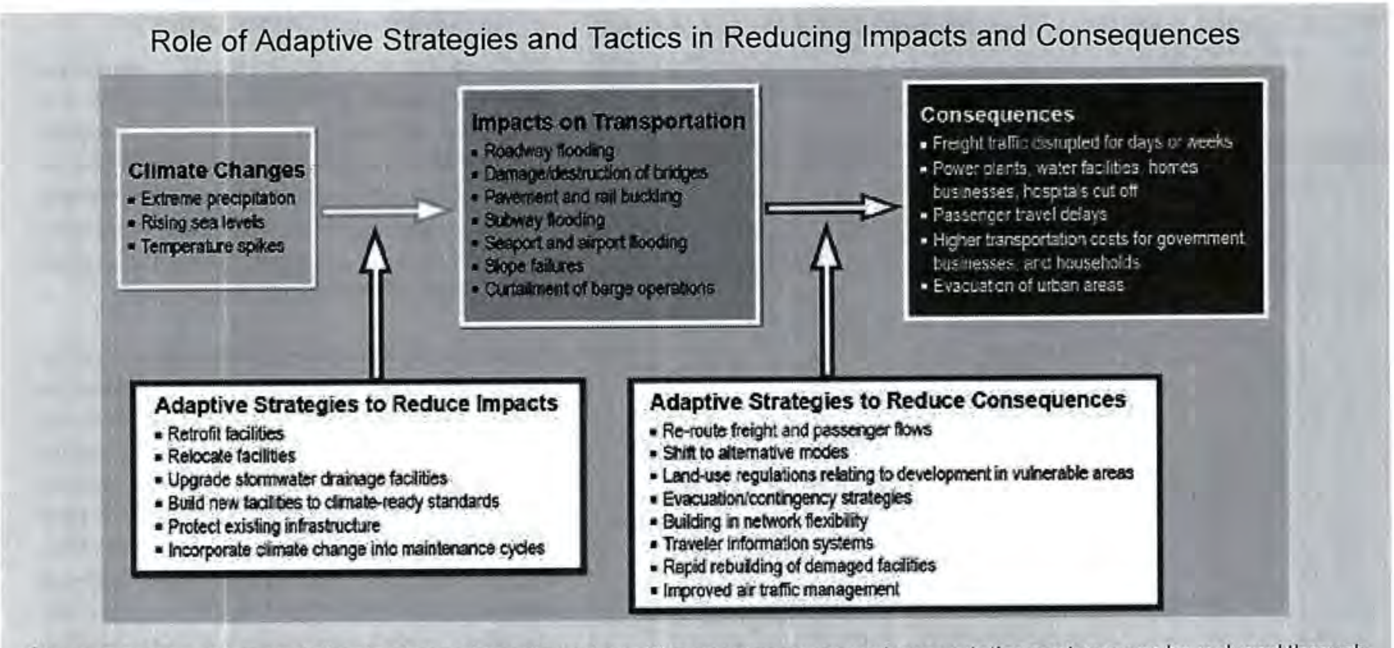

Figure 5.5. Many projected climate change impacts and resulting consequences on transportation systems can be reduced through a combination of infrastructure modifications, improved information systems, and policy changes.

include improvements in storm water management, coastal zone management, and coastal evacuation plans.

At the national level, the transportation network has some capability to adjust to climate-related disruptions due to the presence of network redundancy – multiple routes are often possible for long-distance travel, and more than one mode of transportation may be used for travel. However, in some cases, only one major route connects major destinations, such as Interstate 5 between Seattle and San Francisco; movements along such links are particularly vulnerable to disruption.

Disruptions to the nation's inland water system from floods or droughts can, and has, totally disrupted barge traffic. Severe droughts throughout the upper Midwest in 2012 reduced flows in the Missouri and Mississippi Rivers to near record low levels, disrupting barge traffic. While alternative modes, such as rail and truck, may alleviate some of these disruptions, it is impractical to shift major product shipments such as Midwest grain to other modes of transportation – at least in the near term.[57]

While extreme weather events will continue to cause flight cancellations and delays, many weather delays from non-extreme events are compounded by existing inadequacies in the current national air traffic management system.[58] Improvements in the air traffic system, such as those anticipated in the FAA's NextGEN (www.faa.gov/nextgen/), should reduce weather-related delays.

At the state and local level, there is less resilience to be gained by alternative routing, and impacts may be more intense. For example, significant local and regional disruption and economic costs could result from the flooding of assets as diverse as New York's subways, Iowa's roads, San Francisco's airports, and Vermont's bridges.

Climate change is one of many factors, and an increasingly important one, that many state, regional, and local agencies are considering as they plan for new and rehabilitated facilities. By incorporating climate change routinely into the planning process, governments can reduce the vulnerability to climate change impacts and take actions that enhance the resilience

WINTER STORM-RELATED CLOSURES OF I-5 AND I-90 IN WASHINGTON STATE, 2007-2008

In December 2007, heavy rainfall west of I-5, combined with melting snow from the mountains, created extremely high floodwaters in western Washington State. Six-hour rainfall amounts were near a 100-year event for areas in Southwest Washington. High winds, heavy rains, mudslides, and falling trees made travel unsafe on highways. Downed power lines blocked roads, and, in many urban areas, rainwater overwhelmed drainage systems and flooded roadways.

The combined economic impact in the I-5 and I-90 corridors was estimated at almost $75 million, of which some $47 million was associated with the I-5 disruption and $28 million with the I-90 corridor. Estimated highway damage from the winter storm was $18 million for state routes and another $39 million for city and county roads.[56]

PLANNING FOR CLIMATE CHANGE

Charlotte County exemplifies how local governments can incorporate aspects of climate change into transportation planning. The Metropolitan Planning Organization in Charlotte County-Punta Gorda, Florida conducted long-range scenario planning that integrated climate change projections.[65] A "smart growth" scenario that concentrated growth in urban centers was compared with a "resilient growth" scenario that steered development away from areas vulnerable to sea level rise. Planners evaluated the scenarios based on projected transportation performance outcomes and selected a preferred scenario reflecting aspects of each alternative.

of the transportation system to adverse weather conditions. Governments at various levels are already taking action, as described below.

Land-use planning can reduce risk by avoiding new development in flood-prone areas, conserving open space to enhance drainage, and relocating or abandoning structures or roads that have experienced repeated flooding. The National Flood Insurance Program encourages buyouts of repetitive loss structures and preservation of open space by reducing flood insurance rates for communities that adopt these practices.

An important step in devising an adaptation plan is to assess vulnerabilities (Ch. 26: Decision Support; Ch. 28: Adaptation). The Federal Highway Administration funded pilot projects in five coastal states to test a conceptual framework for evaluating risk.[59] The framework identifies transportation assets, evaluates the likelihood of impact on specific assets, and assesses the seriousness of such impacts.

Several state and local governments have conducted additional vulnerability assessments that identify potential impacts to transportation systems, especially in coastal areas. Detailed assessment work has been undertaken by New York City,[40,42,60] California,[61] Massachusetts,[62] Washington,[63] Florida, and Boston.[64]

Non-coastal states and regions have also begun to produce vulnerability assessments. Midwestern states, including Wisconsin[66] Iowa,[67] and Michigan,[68] have addressed increasing risk of flooded roadways and other impacts.

Transit systems are already implementing measures that reduce vulnerability to climate impacts, including rail buckling. Portland, Oregon's transit agency has been installing expansion joints at vulnerable locations, improving reliability of rail

TROPICAL STORM IRENE DEVASTATES VERMONT TRANSPORTATION IN AUGUST 2011

In August of 2011, Vermont was inundated with rain and massive flooding from Tropical Storm Irene (see also Ch.16: Northeast, "Hurricane Vulnerability"), closing down 146 segments of the state road system along with more than 200 bridges, and costing an estimated $175 to $200 million to rebuild state highways and bridges. An additional 2,000 or more municipal roads and nearly 1,000 culverts were damaged, and more than 200 miles of state-owned rail required repair.[75]

The volume of water was unprecedented, as was the power of the water in the rivers running through the state. Culverts and bridges were affected and slope stability was threatened as a result of the immense amount and power of water and subsequent flooding.

Tropical Storm Impact on Vermont Road

Figure 5.6. Vermont Route 131, outside Cavendish, a week after Tropical Storm Irene unleashed severe precipitation and flooding that damaged many Vermont roads, bridges, and rail lines. (Photo credit: Vermont Agency of Transportation).

When asked about the lessons learned, the Vermont Agency of Transportation (VTrans) indicated the importance of good maintenance of riverbeds as well as roads. VTrans is working with the Vermont Agency of Natural Resources, looking upstream and downstream at the structure of the rivers, recognizing that risk reduction may involve managing rivers as much as changing bridges or roadways.

Rich Tetreault of VTrans emphasized that "Certainly we will be looking to right-size the bridges and culverts that need to be replaced ... Knowing that we do not have the funds to begin wholesale rebuilding of the entire highway network to withstand future flooding, we will also enhance our ability to respond" when future flooding occurs.[74]

AP Photo/The [illegible]-Pilot, [illegible]e Earley

Storm surge on top of rising sea levels have damaged roads and other coastal infrastructure.

service.[14] In New York, ventilation grates are being elevated to reduce the risk of flooding.[40]

Transportation agencies are incorporating climate change into ongoing design activities. For example, the Alaska Department of Transportation (DOT) spends more than $10 million annually on shoreline protection, relocations, and permafrost protection for roadways (see "Thawing Alaska").[25] In May 2011, the California Department of Transportation (Caltrans) issued guidance to their staff on whether and how to incorporate sea level rise into new project designs.[69]

States have begun to integrate climate impacts into Transportation Asset Management, a systematic process for monitoring the conditions of roads and transit facilities.[18,70] Maryland is working to prioritize assets taking sea level rise and increased storm intensity into account and is developing a tool to track assets and assess vulnerability.[71] Florida DOT continually monitors conditions on roads and bridges and is developing a statewide inventory and action plan for high-risk bridges.[72] Among inland states, Michigan DOT has identified a wide range of operational and asset management changes to adjust to climate change.[68] Planting street trees has been shown to reduce the urban heat island effect and reduce heat stress on pavement.[73]

Effective stormwater and stream/river management can reduce the risk of flooding for transportation infrastructure. Following Tropical Storm Irene, Vermont state agencies are working on stream and river management to reduce conditions that exacerbate flooding impacts on transportation.[74]

Effective asset management requires significant data and monitoring of transportation assets. Improved weather and road-condition information systems enable transportation system managers to anticipate and detect problems better and faster – enabling them to close systems if needed, alert motorists, and dispatch maintenance and snow-removal crews. As Michigan DOT has noted, an increase in lake-effect snows means that existing models used for snow and ice removal procedures are no longer reliable, requiring better monitoring and new models, as well as better roadway condition detection systems.[68]

Similarly, regular maintenance and cleaning of urban levee and culvert systems reduces the risk of roads and rails being inundated by flooding.

Extreme weather, such as hurricanes or intense storms, stresses transportation at precisely the time when smooth operation is critical. Effective evacuation planning, including early warning systems, coordination across jurisdictional boundaries, and creating multiple evacuation routes builds preparedness. Identifying areas with high concentrations of vulnerable and special-needs populations (including elderly, disabled, and transit-dependent groups) enhances readiness, as does identifying assets such as school buses or other transit vehicles that can be deployed for households that do not own vehicles.

5: TRANSPORTATION

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