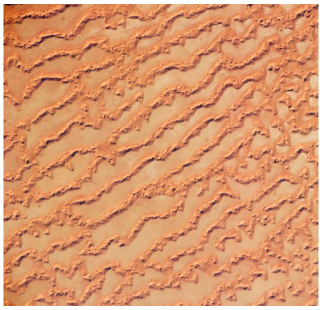

6
Temperature Changes in the United States

KEY FINDINGS

1. Annual average temperature over the contiguous United States has increased by 1.2°F (0.7°C) for the period 1986–2016 relative to 1901–1960 and by 1.8°F (1.0°C) based on a linear regression for the period 1895–2016 (*very high confidence*). Surface and satellite data are consistent in their depiction of rapid warming since 1979 (*high confidence*). Paleo-temperature evidence shows that recent decades are the warmest of the past 1,500 years (*medium confidence*).

2. There have been marked changes in temperature extremes across the contiguous United States. The frequency of cold waves has decreased since the early 1900s, and the frequency of heat waves has increased since the mid-1960s. The Dust Bowl era of the 1930s remains the peak period for extreme heat. The number of high temperature records set in the past two decades far exceeds the number of low temperature records. (*Very high confidence*)

3. Annual average temperature over the contiguous United States is projected to rise (*very high confidence*). Increases of about 2.5°F (1.4°C) are projected for the period 2021–2050 relative to 1976–2005 in all RCP scenarios, implying recent record-setting years may be "common" in the next few decades (*high confidence*). Much larger rises are projected by late century (2071–2100): 2.8°–7.3°F (1.6°–4.1°C) in a lower scenario (RCP4.5) and 5.8°–11.9°F (3.2°–6.6°C) in the higher scenario (RCP8.5) (*high confidence*).

4. Extreme temperatures in the contiguous United States are projected to increase even more than average temperatures. The temperatures of extremely cold days and extremely warm days are both expected to increase. Cold waves are projected to become less intense while heat waves will become more intense. The number of days below freezing is projected to decline while the number above 90°F will rise. (*Very high confidence*)

Recommended Citation for Chapter

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Introduction

Temperature is among the most important climatic elements used in decision-making. For example, builders and insurers use temperature data for planning and risk management while energy companies and regulators use temperature data to predict demand and set utility rates. Temperature is also a key indicator of climate change: recent increases are apparent over the land, ocean, and troposphere, and substantial changes are expected for this century. This chapter summarizes the major observed and projected changes in near-surface air temperature over the United States, emphasizing new data sets and model projections since the Third National Climate Assessment (NCA3). Changes are depicted using a spectrum of observations, including surface weather stations, moored ocean buoys, polar-orbiting satellites, and temperature-sensitive proxies. Projections are based on global models and downscaled products from CMIP5 (Coupled Model Intercomparison Project Phase 5) using a suite of Representative Concentration Pathways (RCPs; see Ch. 4: Projections for more on RCPs and future scenarios).

6.1 Historical Changes

6.1.1 Average Temperatures

Changes in average temperature are described using a suite of observational datasets. As in NCA3, changes in land temperature are assessed using the nClimGrid dataset.[1, 2] Along U.S. coastlines, changes in sea surface temperatures are quantified using a new reconstruction[3] that forms the ocean component of the NOAA Global Temperature dataset.[4] Changes in middle tropospheric temperature are examined using updated versions of multiple satellite datasets.[5, 6, 7]

The annual average temperature of the contiguous United States has risen since the start of the 20th century. In general, temperature increased until about 1940, decreased until about 1970, and increased rapidly through 2016. Because the increase was not constant over time, multiple methods were evaluated in this report (as in NCA3) to quantify the trend. All methods yielded rates of warming that were significant at the 95% level. The lowest estimate of 1.2°F (0.7°C) was obtained by computing the difference between the average for 1986–2016 (i.e., present-day) and the average for 1901–1960 (i.e., the first half of the last century). The highest estimate of 1.8°F (1.0°C) was obtained by fitting a linear (least-squares) regression line through the period 1895–2016. Thus, the temperature increase cited in this assessment is 1.2°–1.8°F (0.7°–1.0°C).

This increase is about 0.1°F (0.06°C) less than presented in NCA3, and it results from the use of slightly different periods in each report. In particular, the decline in the lower bound stems from the use of different time periods to represent present-day climate (NCA3 used 1991–2012, which was slightly warmer than the 1986–2016 period used here). The decline in the upper bound stems mainly from temperature differences late in the record (e.g., the last year of data available for NCA3 was 2012, which was the warmest year on record for the contiguous United States).

Each NCA region experienced a net warming through 2016 (Table 6.1). The largest changes were in the western United States, where average temperature increased by more than 1.5°F (0.8°C) in Alaska, the Northwest, the Southwest, and also in the Northern Great Plains. As noted in NCA3, the Southeast had the least warming, driven by a combination of natural variations and human influences.[8] In most regions, average minimum temperature increased at a slightly higher rate than average maximum temperature, with the Midwest having the largest discrepancy, and the Southwest and Northwest having the smallest. This differential rate of warming resulted in a continuing

Table 6.1. Observed changes in annual average temperature (°F) for each National Climate Assessment region. Changes are the difference between the average for present-day (1986–2016) and the average for the first half of the last century (1901–1960 for the contiguous United States, 1925–1960 for Alaska, Hawai'i, and the Caribbean). Estimates are derived from the nClimDiv dataset[1,2].

NCA Region	Change in Annual Average Temperature	Change in Annual Average Maximum Temperature	Change in Annual Average Minimum Temperature
Contiguous U.S.	1.23°F	1.06°F	1.41°F
Northeast	1.43°F	1.16°F	1.70°F
Southeast	0.46°F	0.16°F	0.76°F
Midwest	1.26°F	0.77°F	1.75°F
Great Plains North	1.69°F	1.66°F	1.72°F
Great Plains South	0.76°F	0.56°F	0.96°F
Southwest	1.61°F	1.61°F	1.61°F
Northwest	1.54°F	1.52°F	1.56°F
Alaska	1.67°F	1.43°F	1.91°F
Hawaii	1.26°F	1.01°F	1.49°F
Caribbean	1.35°F	1.08°F	1.60°F

decrease in the diurnal temperature range that is consistent with other parts of the globe.[9] Annual average sea surface temperature also increased along all regional coastlines (see Figure 1.3), though changes were generally smaller than over land owing to the higher heat capacity of water. Increases were largest in Alaska (greater than 1.0°F [0.6°C]) while increases were smallest (less than 0.5°F [0.3°C]) in coastal areas of the Southeast.

More than 95% of the land surface of the contiguous United States had an increase in annual average temperature (Figure 6.1). In contrast, only small (and somewhat dispersed) parts of the Southeast and Southern Great Plains experienced cooling. From a seasonal perspective, warming was greatest and most widespread in winter, with increases of over 1.5°F (0.8°C) in most areas. In summer, warming was less extensive (mainly along the East Coast and in the western third of the Nation), while cooling was evident in parts of the Southeast, Midwest, and Great Plains.

There has been a rapid increase in the average temperature of the contiguous United States over the past several decades. There is general consistency on this point between the surface thermometer record from NOAA[1] and the middle tropospheric satellite records from Remote Sensing Systems (RSS),[5] NOAA's Center for Satellite Applications and Research (STAR),[7] and the University of Alabama in Huntsville (UAH).[6] In particular, for the period 1979–2016, the rate of warming in the surface record was 0.512°F (0.284°C) per decade, versus trends of 0.455°F (0.253°C), 0.421°F (0.234°C), and 0.289°F (0.160 °C) per decade for RSS version 4, STAR version 3, and UAH version 6, respectively (after accounting for stratospheric influences). All trends are statistically significant at the 95% level. For the contiguous United States, the year 2016 was the second-warmest on record at the surface and in the middle troposphere (2012 was the warmest year at the surface, and 2015 was the warmest in the middle troposphere). Generally speaking, surface and satellite records

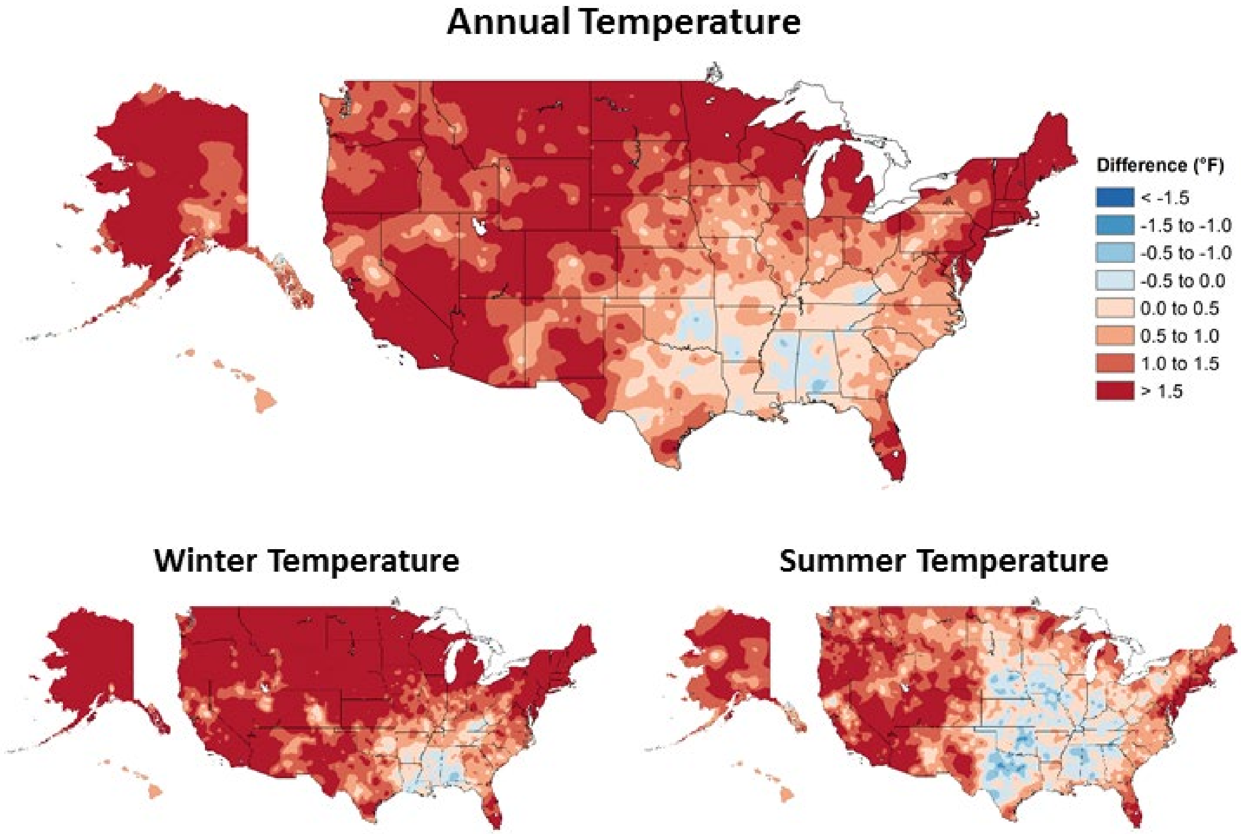

Figure 6.1. Observed changes in annual, winter, and summer temperature (°F). Changes are the difference between the average for present-day (1986–2016) and the average for the first half of the last century (1901–1960 for the contiguous United States, 1925–1960 for Alaska and Hawai'i). Estimates are derived from the nClimDiv dataset.[1, 2] (Figure source: NOAA/NCEI).

do not have identical trends because they do not represent the same physical quantity; surface measurements are made using thermometers in shelters about 1.5 meters above the ground whereas satellite measurements are mass-weighted averages of microwave emissions from deep atmospheric layers. The UAH record likely has a lower trend because it differs from the other satellite products in the treatment of target temperatures from the NOAA-9 satellite as well as in the correction for diurnal drift.[10]

Recent paleo-temperature evidence confirms the unusual character of wide-scale warming during the past few decades as determined from the instrumental record. The most important new paleoclimate study since NCA3 showed that for each of the seven continental regions, the reconstructed area-weighted average temperature for 1971–2000 was higher than for any other time in nearly 1,400 years,[11] although with significant uncertainty around the central estimate that leads to this conclusion. Recent (up to 2006) 30-year smoothed temperatures across temperate North America (including most of the continental United States) are similarly reconstructed as the warmest over the past 1,500 years[12] (Figure 6.2). Unlike the PAGES 2k seven-continent result mentioned above, this conclusion for North America is robust in relation to the estimated uncertainty range. Reconstruction data since 1500 for western temperate North America show the same conclusion at the annual time scale for 1986–2005. This time period and the running 20-year periods thereafter are warmer than all possible continuous 20-year sequences in a 1,000-member statistical reconstruction ensemble.[13]

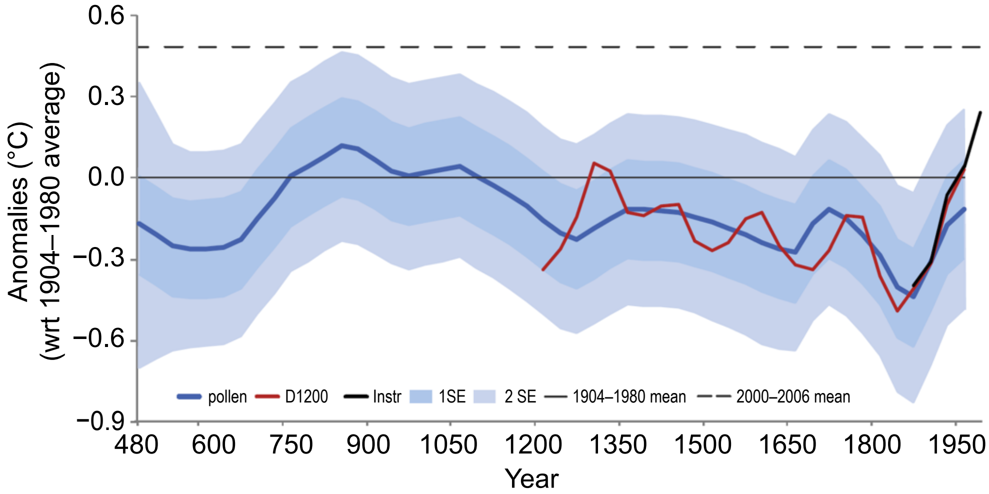

Figure 6.2. Pollen-based temperature reconstruction for temperate North America. The blue curve depicts the pollen-based reconstruction of 30-year averages (as anomalies from 1904 to 1980) for the temperate region (30°–55°N, 75°–130°W). The red curve shows the corresponding tree ring-based decadal average reconstruction, which was smoothed and used to calibrate the lower-frequency pollen-based estimate. Light (medium) blue zones indicate 2 standard error (1 standard error) uncertainty estimations associated with each 30-year value. The black curve shows comparably smoothed instrumental temperature values up to 1980. The dashed black line represents the average temperature anomaly of comparably smoothed instrumental data for the period 2000–2006. (Figure source: NOAA NCEI).

6.1.2 Temperature Extremes

Shifts in temperature extremes are examined using a suite of societally relevant climate change indices[14, 15] derived from long-term observations of daily surface temperature.[16] The coldest and warmest temperatures of the year are of particular relevance given their widespread use in engineering, agricultural, and other sectoral applications (for example, extreme annual design conditions by the American Society of Heating, Refrigeration, and Air Conditioning; plant hardiness zones by the U.S. Department of Agriculture). Cold waves and heat waves (that is, extended periods of below or above normal temperature) are likewise of great importance because of their numerous societal and environmental impacts, which span from human health to plant and animal phenology. Changes are considered for a spectrum of event frequencies and intensities, ranging from the typical annual extreme to the 1-in-10 year event (an extreme that only has a 10% chance of occurrence in any given year). The discussion focuses on the contiguous United States; Alaska, Hawai‘i, and the Caribbean do not have a sufficient number of long-term stations for a century-scale analysis.

Cold extremes have become less severe over the past century. For example, the coldest daily temperature of the year has increased at most locations in the contiguous United States (Figure 6.3). All regions experienced net increases (Table 6.2), with the largest rises in the Northern Great Plains and the Northwest (roughly 4.5°F [2.5°C]), and the smallest in the Southeast (about 1.0°F [0.6°C]). In general, there were increases throughout the record, with a slight acceleration in recent decades (Figure 6.3). The temperature of extremely cold days (1-in-10 year events) generally exhibited the same pattern of increases as the coldest daily temperature of the year. Consistent with these increases, the number of cool nights per year (those with a minimum temperature below the 10th percentile for 1961–1990) declined in all regions, with much of the West having decreases of roughly two weeks. The frequency of cold waves (6-day periods with a minimum temperature below the

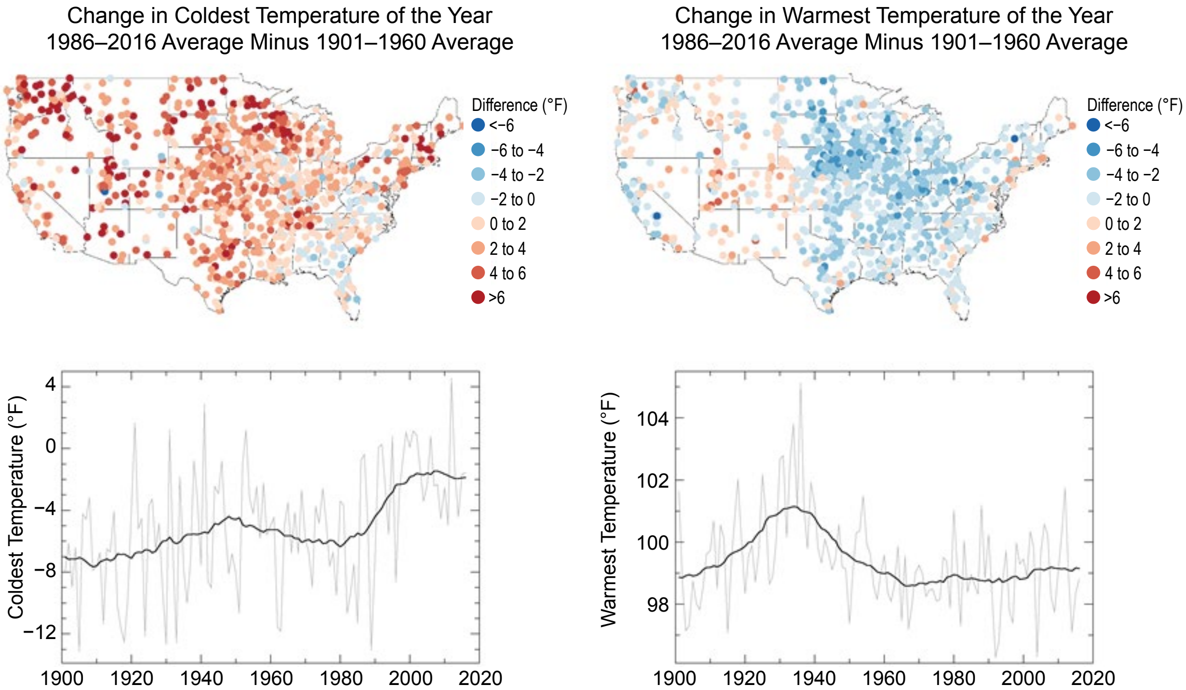

Figure 6.3. Observed changes in the coldest and warmest daily temperatures (°F) of the year in the contiguous United States. Maps (top) depict changes at stations; changes are the difference between the average for present-day (1986–2016) and the average for the first half of the last century (1901–1960). Time series (bottom) depict the area-weighted average for the contiguous United States. Estimates are derived from long-term stations with minimal missing data in the Global Historical Climatology Network–Daily dataset.[16] (Figure source: NOAA/NCEI).

Table 6.2. Observed changes in the coldest and warmest daily temperatures (°F) of the year for each National Climate Assessment region in the contiguous United States. Changes are the difference between the average for present-day (1986–2016) and the average for the first half of the last century (1901–1960). Estimates are derived from long-term stations with minimal missing data in the Global Historical Climatology Network–Daily dataset.[16]

NCA Region	Change in Coldest Day of the Year	Change in Warmest Day of the Year
Northeast	2.83°F	−0.92°F
Southeast	1.13°F	−1.49°F
Midwest	2.93°F	−2.22°F
Great Plains North	4.40°F	−1.08°F
Great Plains South	3.25°F	−1.07°F
Southwest	3.99°F	0.50°F
Northwest	4.78°F	−0.17°F

10th percentile for 1961–1990) has fallen over the past century (Figure 6.4). The frequency of intense cold waves (4-day, 1-in-5 year events) peaked in the 1980s and then reached record-low levels in the 2000s.[17]

Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year increased in some parts of the West over the past century (Figure 6.3), but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease (Table 6.2), most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). The decreases in the eastern half of Nation, particularly in the Great Plains, are mainly tied to the unprecedented summer heat of the 1930s Dust Bowl era, which was exacerbated by land-surface feedbacks driven by springtime

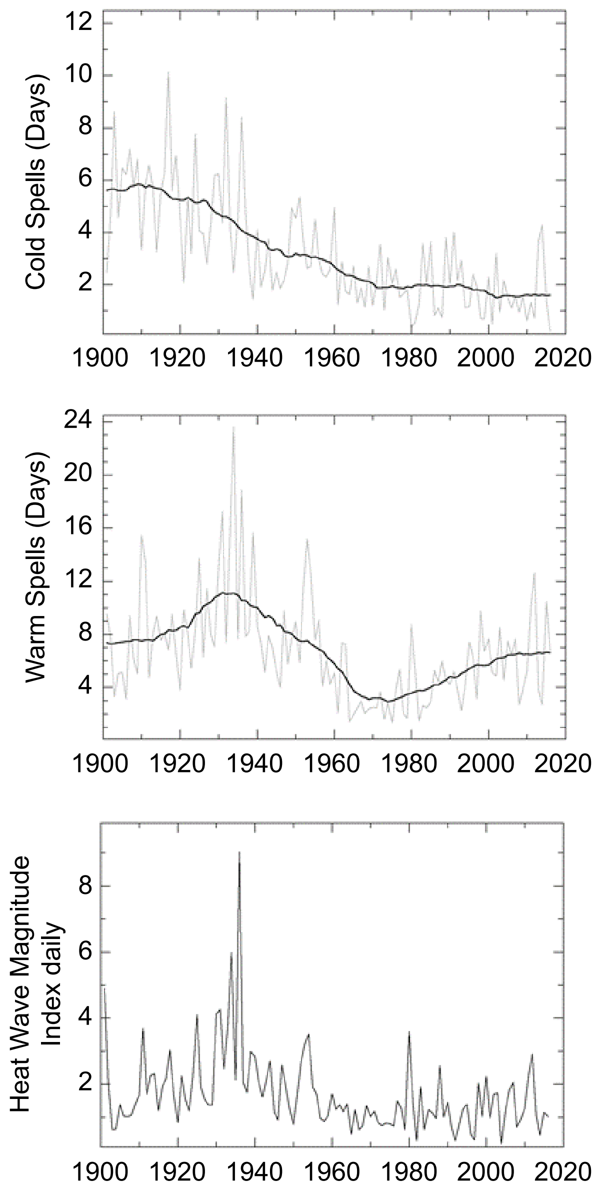

Figure 6.4. Observed changes in cold and heat waves in the contiguous United States. The top panel depicts changes in the frequency of cold waves; the middle panel depicts changes in the frequency of heat waves; and the bottom panel depicts changes in the intensity of heat waves. Cold and heat wave frequency indices are defined in Zhang et al.,[15] and the heat wave intensity index is defined in Russo et al.[14] Estimates are derived from long-term stations with minimal missing data in the Global Historical Climatology Network–Daily dataset.[16] (Figure source: NOAA/NCEI).

precipitation deficits and land mismanagement.[18] However, anthropogenic aerosol forcing may also have reduced summer temperatures in the Northeast and Southeast from the early 1950s to the mid-1970s,[19] and agricultural intensification may have suppressed the hottest extremes in the Midwest.[20] Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter (Figure 6.4). As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s. The frequency of intense heat waves (4-day, 1-in-5 year events) has generally increased since the 1960s in most regions except the Midwest and the Great

Plains.[17,21] Since the early 1980s (Figure 6.4), there is suggestive evidence of a slight increase in the intensity of heat waves nationwide[14] as well as an increase in the concurrence of droughts and heat waves.[22]

Changes in the occurrence of record-setting daily temperatures are also apparent. Very generally, the number of record lows has been declining since the late-1970s while the number of record highs has been rising.[23] By extension, there has been an increase in the ratio of the number of record highs to record lows (Figure 6.5). Over the past two decades, the average of this ratio exceeds two (meaning that twice as many high-temperature records have been set as low-temperature records). The number of new highs has surpassed the number of new lows in 15 of the last 20 years, with 2012 and 2016 being particularly extreme (ratios of seven and five, respectively).

6.2 Detection and Attribution

6.2.1 Average Temperatures

While a confident attribution of global temperature increases to anthropogenic forcing has been made,[24] detection and attribution assessment statements for smaller regions are generally much weaker. Nevertheless, some detectable anthropogenic influences on average temperature have been reported for North America and parts of the United States (e.g., Christidis et al. 2010;[25] Bonfils et al. 2008;[26] Pierce et al. 2009[27]). Figure 6.6 shows an example for linear trends for 1901–2015, indicating a detectable anthropogenic warming since 1901 over the western and northern regions of the contiguous United States for the CMIP5 multimodel ensemble—a condition that was also met for most of the individual models.[28] The Southeast stands out as the only region with no "detectable" warming since 1901; observed trends there were inconsistent with CMIP5 All Forcing historical runs.[28] The cause

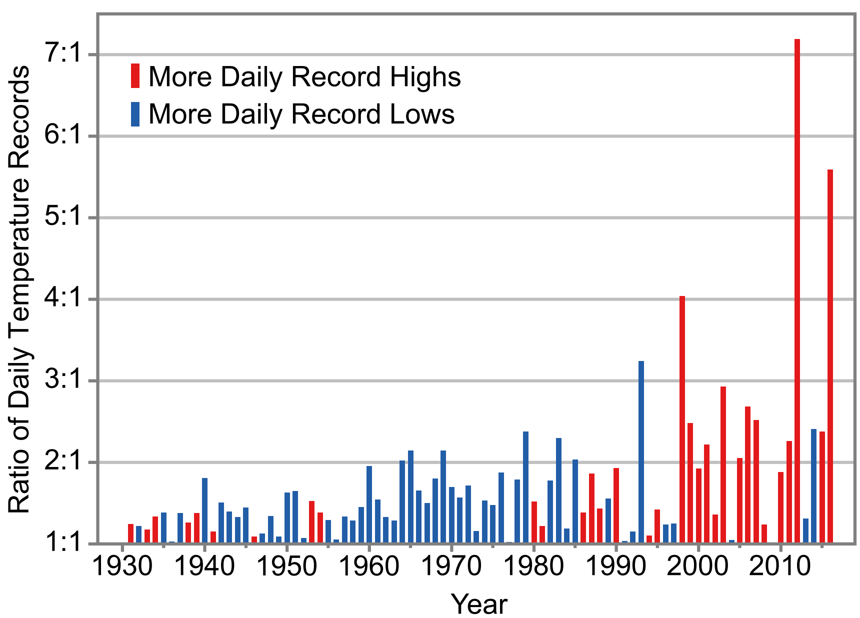

Figure 6.5. Observed changes in the occurrence of record-setting daily temperatures in the contiguous United States. Red bars indicate a year with more daily record highs than daily record lows, while blue bars indicate a year with more record lows than highs. The height of the bar indicates the ratio of record highs to lows (red) or of record lows to highs (blue). For example, a ratio of 2:1 for a blue bar means that there were twice as many record daily lows as daily record highs that year. Estimates are derived from long-term stations with minimal missing data in the Global Historical Climatology Network–Daily dataset.[16] (Figure source: NOAA/NCEI).

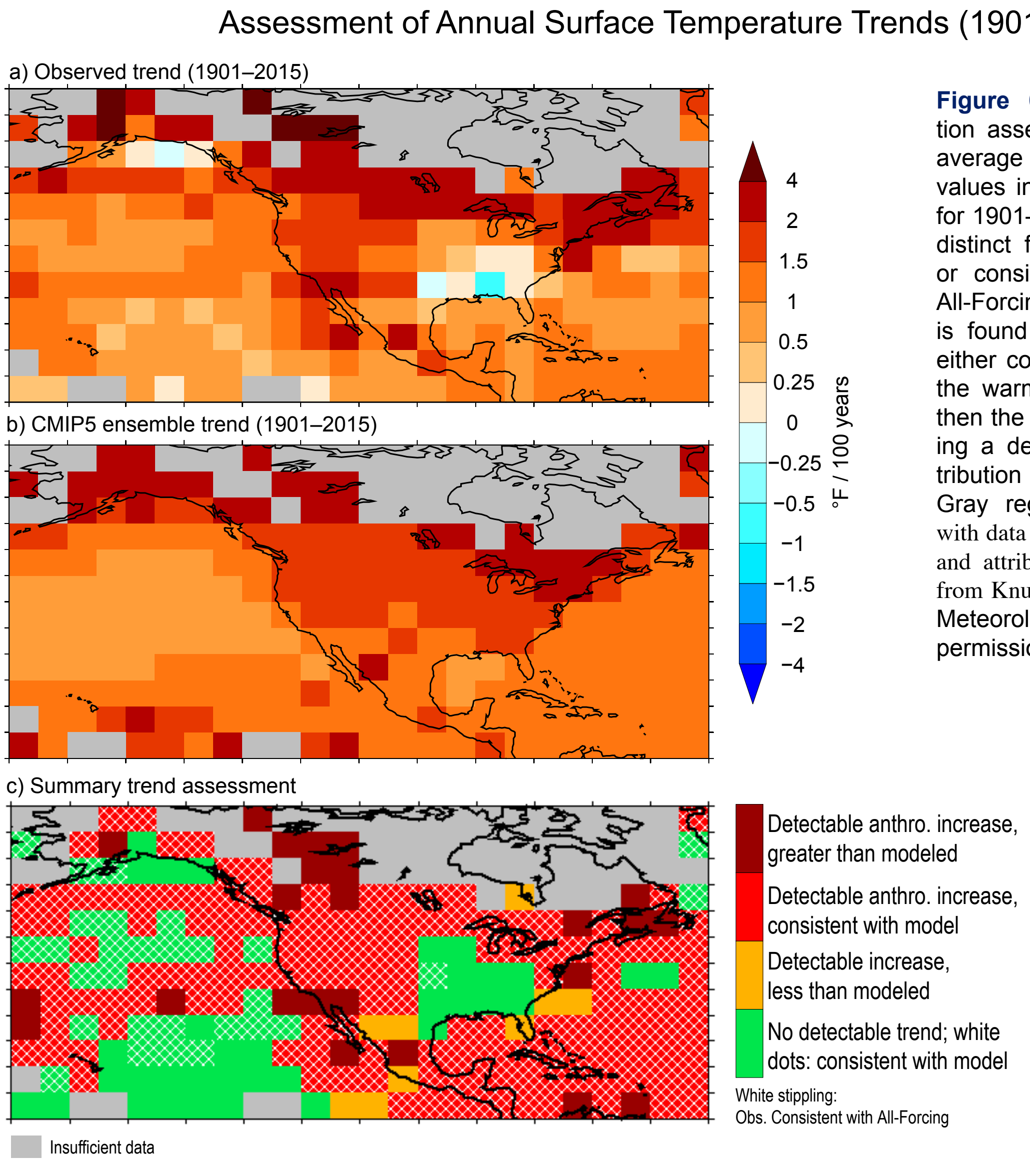

Figure 6.6. Detection and attribution assessment of trends in annual average temperature (°F). Grid-box values indicate whether linear trends for 1901–2015 are detectable (that is, distinct from natural variability) and/or consistent with CMIP5 historical All-Forcing runs. If the grid-box trend is found to be both detectable and either consistent with or greater than the warming in the All-Forcing runs, then the grid box is assessed as having a detectable anthropogenic contribution to warming over the period. Gray regions represent grid boxes with data that are too sparse for detection and attribution. (Figure source: updated from Knutson et al. 2013;[28] © American Meteorological Society. Used with permission.)

of this "warming hole," or lack of a long-term warming trend, remains uncertain, though it is likely a combination of natural and human causes. Some studies conclude that changes in anthropogenic aerosols have played a crucial role (e.g., Leibensperger et al. 2012;[29, 30] Yu et al. 2014[31]), whereas other studies infer a possible large role for atmospheric circulation,[32] internal climate variability (e.g., Meehl et al. 2012;[8] Knutson et al. 2013[28]), and changes in land use (e.g., Goldstein et al. 2009;[33] Xu et al. 2015[34]). Notably, the Southeast has been warming rapidly since the early 1960s.[35, 36] In summary, there is medium confidence for detectable anthropogenic warming over the western and northern regions of the contiguous United States.

6.2.2 Temperature Extremes

The Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (AR5)[24] concluded that it is very likely that human influence has contributed to the observed changes in frequency and intensity of temperature extremes on the global scale since the mid-20th century. The combined influence of anthropogenic and natural forcings was also detectable (medium confidence) over large subregions of North America (e.g., Zwiers et al. 2011;[37] Min et al. 2013[38]). In general, however, results for the contiguous United States are not as compelling as for global land areas, in part because detection of changes in U.S. regional temperature extremes is affected by extreme temperature in the 1930s.[17] Table 6.3 summarizes available attribution statements for recent extreme U.S. temperature events. As an example, the recent record or near-record high March–May average temperatures occurring in 2012 over the eastern United States were attributed in part to external (natural plus anthropogenic) forcing;[39] the century-scale trend response of temperature to external forcing is typically a close approximation to the anthropogenic forcing response alone. Another study found that although the extreme March 2012 warm anomalies over the United States were mostly due to natural variability, anthropogenic warming contributed to the severity.[40] Such statements reveal that both natural and anthropogenic factors influence the severity of extreme temperature events. Nearly every modern analysis of current extreme hot and cold events reveals some degree of attributable human influence.

6.3 Projected Changes

6.3.1 Average Temperatures

Temperature projections are based on global model results and associated downscaled products from CMIP5 using a suite of Representative Concentration Pathways (RCPs). In contrast to NCA3, model weighting is employed to refine projections of temperature for each RCP (Ch. 4: Projections; Appendix B: Model Weighting). Weighting parameters are based on model independence and skill over North America for seasonal temperature and annual extremes. Unless stated otherwise, all changes presented here represent the weighted multimodel mean. The weighting scheme helps refine confidence and likelihood statements, but projections of U.S. surface air temperature remain very similar to those in NCA3. Generally speaking, extreme temperatures are projected to increase even more than average temperatures.[41]

Table 6.3. Extreme temperature events in the United States for which attribution statements have been made. There are three possible attribution statements: "+" shows an attributable human-induced increase in frequency or intensity, "−" shows an attributable human-induced decrease in frequency or intensity, "0" shows no attributable human contribution.

Study	Period	Region	Type	Statement
Rupp et al. 2012[52] Angélil et al. 2017[53]	Spring/Summer 2011	Texas	Hot	+ +
Hoerling et al. 2013[54]	Summer 2011	Texas	Hot	+
Diffenbaugh and Scherer 2013[55] Angélil et al. 2017[53]	July 2012	Northcentral and Northeast	Hot	+ +
Cattiaux and Yiou 2013[56] Angélil et al. 2017[53]	Spring 2012	East	Hot	0 +
Knutson et al. 2013b[39] Angélil et al. 2017[53]	Spring 2012	East	Hot	+ +
Jeon et al 2016[57]	Summer 2011	Texas/ Oklahoma	Hot	+
Dole et al. 2014[40]	March 2012	Upper Midwest	Hot	+
Seager et al. 2014[58]	2011–2014	California	Hot	+
Wolter et al. 2015[59]	Winter 2014	Midwest	Cold	−
Trenary et al. 2015[60]	Winter 2014	East	Cold	0

The annual average temperature of the contiguous United States is projected to rise throughout the century. Increases for the period 2021–2050 relative to 1976–2005 are projected to be about 2.5°F (1.4°C) for a lower scenario (RCP4.5) and 2.9°F (1.6°C) for the higher scenario (RCP8.5); the similarity in warming reflects the similarity in greenhouse gas concentrations during this period (Figure 4.1). Notably, a 2.5°F (1.4°C) increase makes the near-term average comparable to the hottest year in the historical record (2012). In other words, recent record-breaking years may be "common" in the next few decades. By late-century (2071–2100), the RCPs diverge significantly, leading to different rates of warming: approximately 5.0°F (2.8°C) for RCP4.5 and 8.7°F (4.8°C) for RCP8.5. Likewise, there are different ranges of warming for each scenario: 2.8°–7.3°F (1.6°–4.1°C) for RCP4.5 and 5.8°–11.9°F (3.2°–6.6°C) for RCP8.5. (The range is defined here as the difference between the average increase in the three coolest models and the average increase in the three warmest models.) For both RCPs, slightly greater increases are projected in summer than winter (except for Alaska), and average maximums will rise slightly faster than average minimums (except in the Southeast and Southern Great Plains).

Statistically significant warming is projected for all parts of the United States throughout the century (Figure 6.7). Consistent with polar amplification, warming rates (and spatial gradients) are greater at higher latitudes. For example, warming is largest in Alaska (more than 12.0°F [6.7°C] in the northern half of the state by late-century under RCP8.5), driven in part by a decrease in snow cover and thus surface albedo. Similarly, northern regions of the contiguous United States have slightly more warming than other regions (roughly 9.0°F [5.5°C] in the Northeast, Midwest, and Northern Great Plains by late-century under RCP8.5; Table 6.4). The Southeast has slightly less warming because of latent heat release from increases in evapotranspiration (as is already evident in the observed record). Warming is smallest in Hawai'i and the Caribbean (roughly 4.0°–6.0°F [2.2°–3.3°C] by late century under RCP8.5) due to the moderating effects of surrounding oceans. From a sub-regional perspective, less warming is projected along the coasts of the contiguous United States, again due to maritime influences, although increases are still substantial. Warming at higher elevations may be underestimated because the resolution of the CMIP5 models does not capture orography in detail.

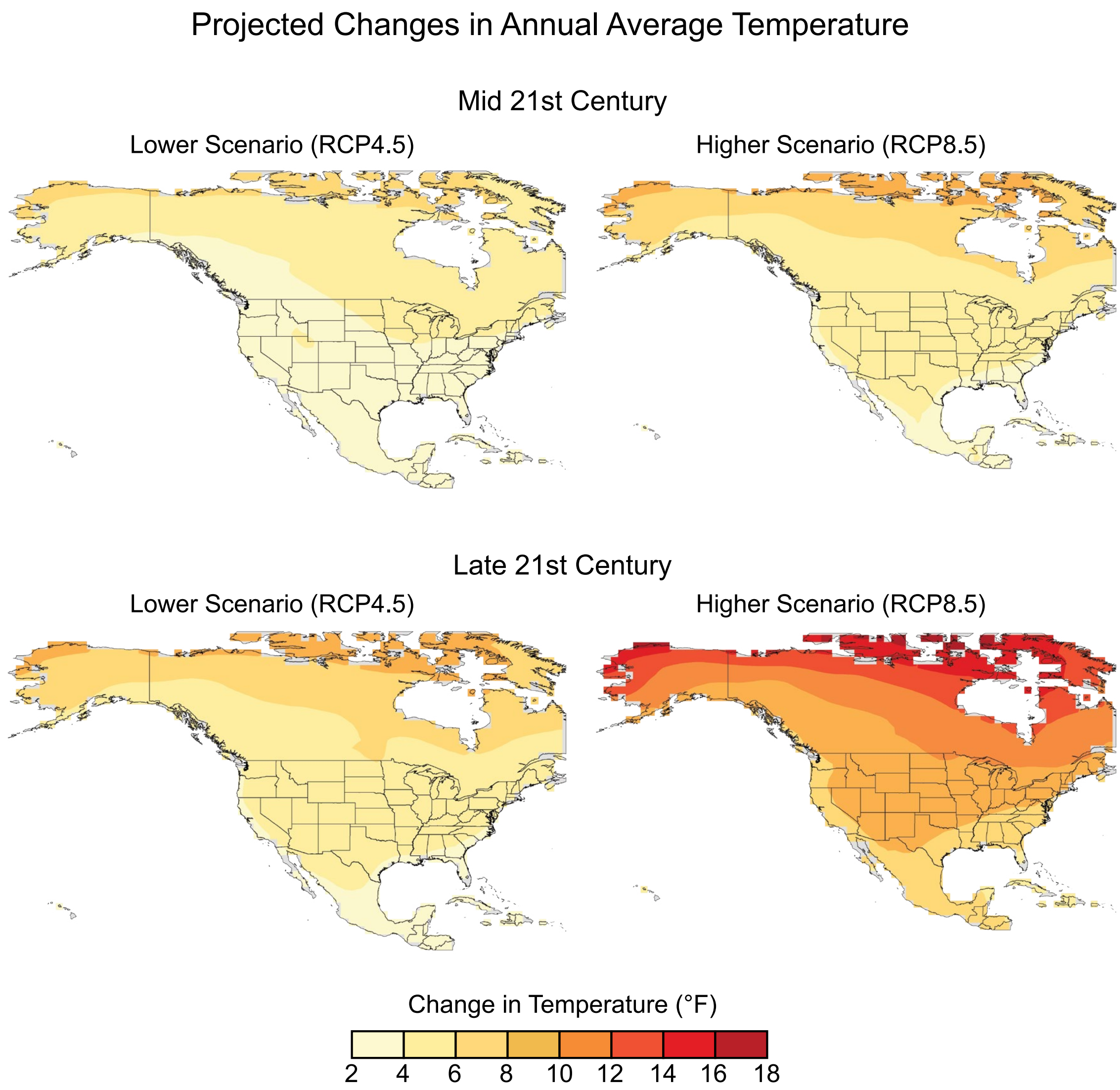

Figure 6.7. Projected changes in annual average temperatures (°F). Changes are the difference between the average for mid-century (2036–2065; top) or late-century (2070–2099, bottom) and the average for near-present (1976–2005). Each map depicts the weighted multimodel mean. Increases are statistically significant in all areas (that is, more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change[45]). (Figure source: CICS-NC and NOAA NCEI).

Table 6.4. Projected changes in annual average temperature (°F) for each National Climate Assessment region in the contiguous United States. Changes are the difference between the average for mid-century (2036–2065) or late-century (2071–2100) and the average for near-present (1976–2005) under the higher scenario (RCP8.5) and a lower scenario (RCP4.5). Estimates are derived from 32 climate models that were statistically downscaled using the Localized Constructed Analogs technique.[51] Increases are statistically significant in all areas (that is, more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change[45]).

NCA Region	RCP4.5 Mid-Century (2036–2065)	RCP8.5 Mid-Century (2036–2065)	RCP4.5 Late-Century (2071–2100)	RCP8.5 Late-Century (2071–2100)
Northeast	3.98°F	5.09°F	5.27°F	9.11°F
Southeast	3.40°F	4.30°F	4.43°F	7.72°F
Midwest	4.21°F	5.29°F	5.57°F	9.49°F
Great Plains North	4.05°F	5.10°F	5.44°F	9.37°F
Great Plains South	3.62°F	4.61°F	4.78°F	8.44°F
Southwest	3.72°F	4.80°F	4.93°F	8.65°F
Northwest	3.66°F	4.67°F	4.99°F	8.51°F

6.3.2 Temperature Extremes

Daily extreme temperatures are projected to increase substantially in the contiguous United States, particularly under the higher scenario (RCP8.5). For instance, the coldest and warmest daily temperatures of the year are expected to increase at least 5°F (2.8°C) in most areas by mid-century,[42] rising to 10°F (5.5°C) or more by late-century.[43] In general, there will be larger increases in the coldest temperatures of the year, especially in the northern half of the Nation, whereas the warmest temperatures will exhibit somewhat more uniform changes geographically (Figure 6.8). By mid-century, the upper bound for projected changes (i.e., the average of the three warmest models) is about 2°F (1.1°C) greater than the weighted multimodel mean. On a regional basis, annual extremes (Table 6.5) are consistently projected to rise faster than annual averages (Table 6.4). Future changes in "very rare" extremes are also striking; by late century, current 1-in-20 year maximums are projected to occur every year, while current 1-in-20 year minimums are not expected to occur at all.[44]

The frequency and intensity of cold waves is projected to decrease while the frequency and intensity of heat waves is projected to increase throughout the century. The frequency of cold waves (6-day periods with a minimum temperature below the 10th percentile) will decrease the most in Alaska and the least in the Northeast while the frequency of heat waves (6-day periods with a maximum temperature above the 90th percentile) will increase in all regions, particularly the Southeast, Southwest, and Alaska. By mid-century, decreases in the frequency of cold waves are similar across RCPs whereas increases in the frequency of heat waves are about 50% greater in the higher scenario (RCP8.5) than the lower scenario (RCP4.5).[45] The intensity of cold waves is projected to decrease while the intensity of heat waves is projected to increase, dramatically so under RCP8.5. By mid-century, both extreme cold waves and extreme heat waves (5-day, 1-in-10 year events) are projected to have temperature increases of at least 11.0°F (6.1°C) nationwide, with larger increases in northern regions (the Northeast, Midwest, Northern Great Plains, and Northwest; Table 6.5).

There are large projected changes in the number of days exceeding key temperature thresholds throughout the contiguous United States.

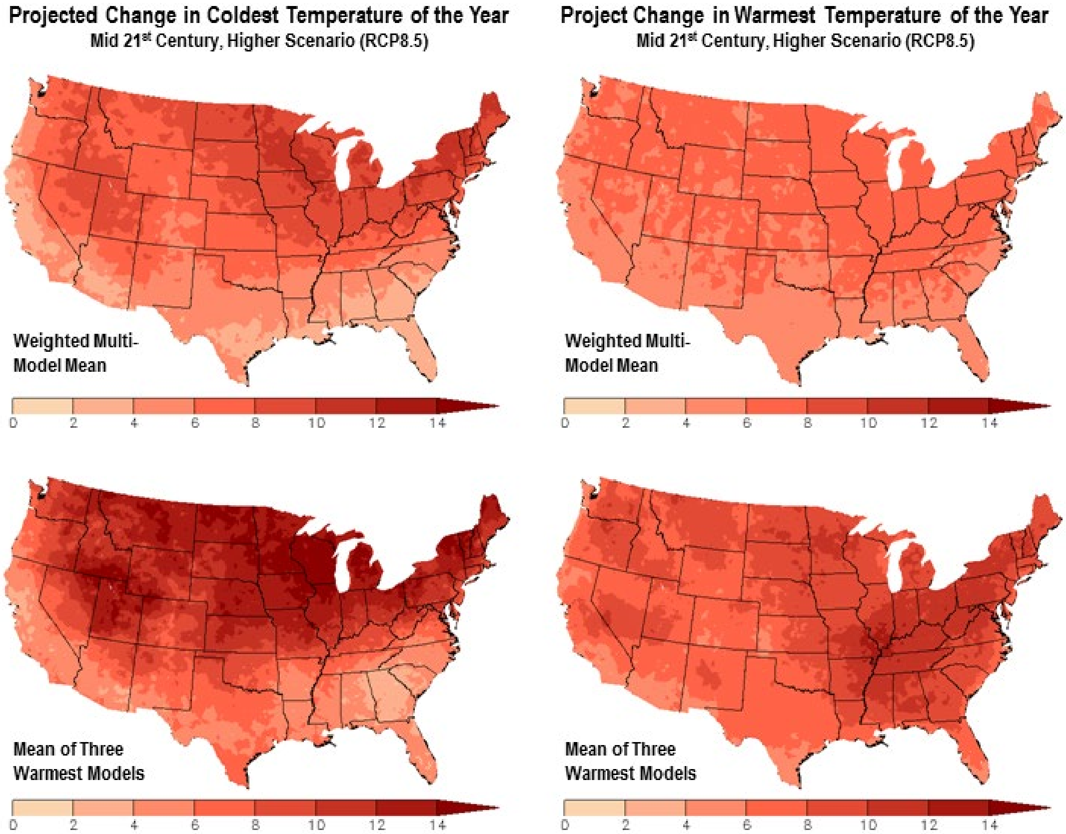

Figure 6.8. Projected changes in the coldest and warmest daily temperatures (°F) of the year in the contiguous United States. Changes are the difference between the average for mid-century (2036–2065) and the average for near-present (1976–2005) under the higher scenario (RCP8.5). Maps in the top row depict the weighted multimodel mean whereas maps on the bottom row depict the mean of the three warmest models (that is, the models with the largest temperature increase). Maps are derived from 32 climate model projections that were statistically downscaled using the Localized Constructed Analogs technique.[51] Increases are statistically significant in all areas (that is, more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change[45]). (Figure source: CICS-NC and NOAA NCEI).

Table 6.5. Projected changes in temperature extremes (˚F) for each National Climate Assessment region in the contiguous United States. Changes are the difference between the average for mid-century (2036–2065) and the average for near-present (1976–2005) under the higher scenario (RCP8.5). Estimates are derived from 32 climate models that were statistically downscaled using the Localized Constructed Analogs technique.[51] Increases are statistically significant in all areas (that is, more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change[45]).

NCA Region	Change in Coldest Day of the Year	Change in Coldest 5-Day 1-in-10 Year Event	Change in Warmest Day of the Year	Change in Warmest 5-Day 1-in-10 Year Event
Northeast	9.51°F	15.93°F	6.51°F	12.88°F
Southeast	4.97°F	8.84°F	5.79°F	11.09°F
Midwest	9.44°F	15.52°F	6.71°F	13.02°F
Great Plains North	8.01°F	12.01°F	6.48°F	12.00°F
Great Plains South	5.49°F	9.41°F	5.70°F	10.73°F
Southwest	6.13°F	10.20°F	5.85°F	11.17°F
Northwest	7.33°F	10.95°F	6.25°F	12.31°F

For instance, there are about 20–30 more days per year with a maximum over 90°F (32°C) in most areas by mid-century under RCP8.5, with increases of 40–50 days in much of the Southeast (Figure 6.9). The upper bound for projected changes is very roughly 10 days greater than the weighted multimodel mean. Consistent with widespread warming, there are 20–30 fewer days per year with a minimum temperature below freezing in the northern and eastern parts of the nation, with decreases of more than 40–50 days in much the West. The upper bound for projected changes in freezing events is very roughly 10–20 days fewer than the weighted multimodel mean in many areas.

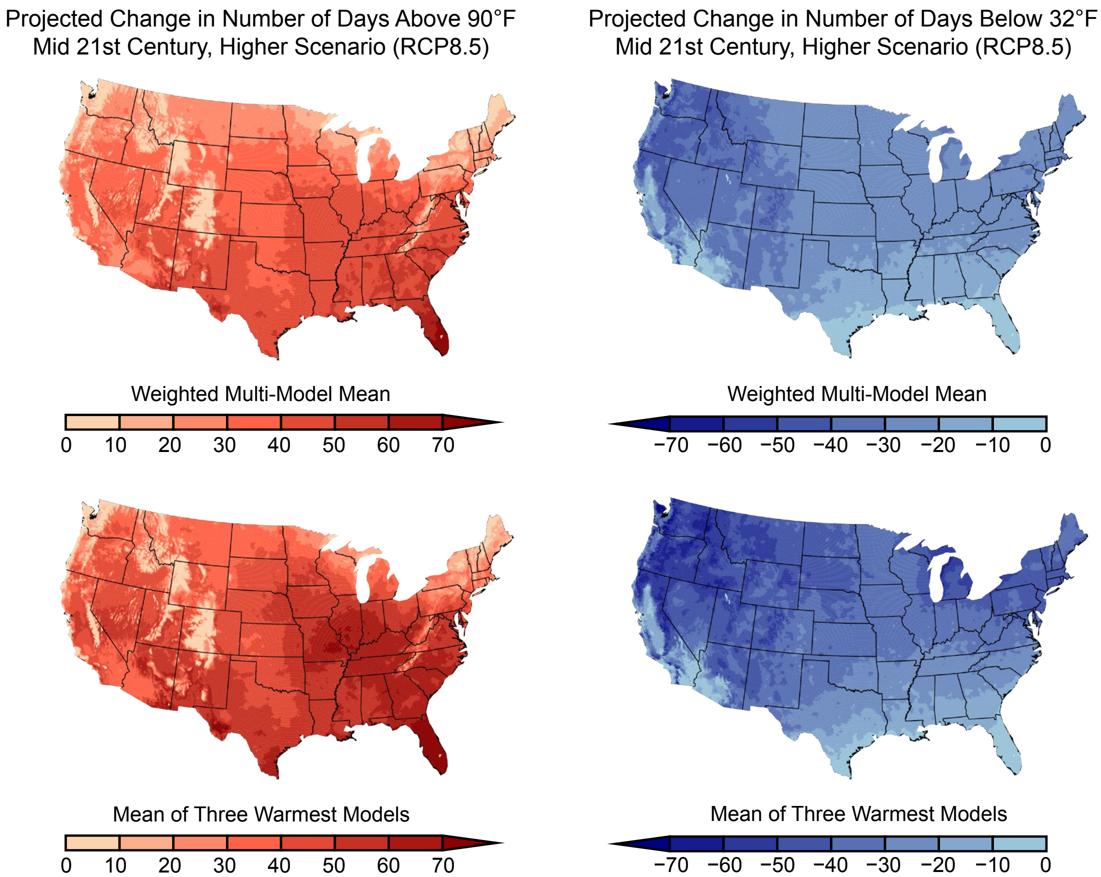

Figure 6.9. Projected changes in the number of days per year with a maximum temperature above 90°F and a minimum temperature below 32°F in the contiguous United States. Changes are the difference between the average for mid-century (2036–2065) and the average for near-present (1976–2005) under the higher scenario (RCP8.5). Maps in the top row depict the weighted multimodel mean whereas maps on the bottom row depict the mean of the three warmest models (that is, the models with the largest temperature increase). Maps are derived from 32 climate model projections that were statistically downscaled using the Localized Constructed Analogs technique.[51] Changes are statistically significant in all areas (that is, more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change[45]). (Figure source: CICS-NC and NOAA NCEI).

TRACEABLE ACCOUNTS

Key Finding 1 Annual average temperature over the contiguous United States has increased by 1.2°F (0.7°C) for the period 1986–2016 relative to 1901–1960 and by 1.8°F (1.0°C) based on a linear regression for the period 1895–2016 (*very high confidence*). Surface and satellite data are consistent in their depiction of rapid warming since 1979 (*high confidence*). Paleo-temperature evidence shows that recent decades are the warmest of the past 1,500 years (*medium confidence*).

Description of Evidence Base

The key finding and supporting text summarize extensive evidence documented in the climate science literature. Similar statements about changes exist in other reports (e.g., NCA3;[46] Global Climate Change Impacts in the United States;[47] SAP 1.1: Temperature trends in the lower atmosphere[48]).

Evidence for changes in U.S. climate arises from multiple analyses of data from in situ, satellite, and other records undertaken by many groups over several decades. The primary dataset for surface temperatures in the United States is nClimGrid,[1, 2] though trends are similar in the U.S. Historical Climatology Network, the Global Historical Climatology Network, and other datasets. Several atmospheric reanalyses (e.g., 20th Century Reanalysis, Climate Forecast System Reanalysis, ERA-Interim, Modern Era Reanalysis for Research and Applications) confirm rapid warming at the surface since 1979, with observed trends closely tracking the ensemble mean of the reanalyses. Several recently improved satellite datasets document changes in middle tropospheric temperatures.[5, 6, 7] Longer-term changes are depicted using multiple paleo analyses (e.g., Wahl and Smerdon 2012;[13] Trouet et al. 2013[12]).

Major Uncertainties

The primary uncertainties for surface data relate to historical changes in station location, temperature instrumentation, observing practice, and spatial sampling (particularly in areas and periods with low station density, such as the intermountain West in the early 20th century). Satellite records are similarly impacted by non-climatic changes such as orbital decay, diurnal sampling, and instrument calibration to target temperatures. Several uncertainties are inherent in temperature-sensitive proxies, such as dating techniques and spatial sampling.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Very high (since 1895), *High* (for surface/satellite agreement since 1979), *Medium* (for paleo)

Likelihood of Impact

Extremely Likely

Summary sentence or paragraph that integrates the above information

There is *very high confidence* in observed changes in average temperature over the United States based upon the convergence of evidence from multiple data sources, analyses, and assessments.

Key Finding 2

There have been marked changes in temperature extremes across the contiguous United States. The frequency of cold waves has decreased since the early 1900s, and the frequency of heat waves has increased since the mid-1960s. The Dust Bowl era of the 1930s remains the peak period for extreme heat. The number of high temperature records set in the past two decades far exceeds the number of low temperature records. (*Very high confidence*)

Description of Evidence Base

The key finding and supporting text summarize extensive evidence documented in the climate science literature. Similar statements about changes have also been made in other reports (e.g., NCA3;[46] SAP 3.3: Weather and Climate Extremes in a Changing Climate;[49] IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation[50]).

Evidence for changes in U.S. climate arises from multiple analyses of in situ data using widely published climate extremes indices. For the analyses presented here, the source of in situ data is the Global Historical Climatology Network–Daily dataset,[16] with changes in extremes being assessed using long-term stations with minimal missing data to avoid network-induced variability on the long-term time series. Cold wave frequency was quantified using the Cold Spell Duration Index,[15] heat wave frequency was quantified using the Warm Spell Duration Index,[15] and heat wave intensity were quantified using the Heat Wave Magnitude Index Daily.[14] Station-based index values were averaged into 4° grid boxes, which were then area-averaged into a time series for the contiguous United States. Note that a variety of other threshold and percentile-based indices were also evaluated, with consistent results (e.g., the Dust Bowl was consistently the peak period for extreme heat). Changes in record-setting temperatures were quantified as in Meehl et al. (2016).[23]

Major Uncertainties

The primary uncertainties for in situ data relate to historical changes in station location, temperature instrumentation, observing practice, and spatial sampling (particularly the precision of estimates of change in areas and periods with low station density, such as the intermountain West in the early 20th century).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Very high

Likelihood of Impact

Extremely likely

Summary sentence or paragraph that integrates the above information

There is *very high confidence* in observed changes in temperature extremes over the United States based upon the convergence of evidence from multiple data sources, analyses, and assessments.

Key Finding 3

Annual average temperature over the contiguous United States is projected to rise (*very high confidence*). Increases of about 2.5°F (1.4°C) are projected for the period 2021–2050 relative to 1976–2005 in all RCP scenarios, implying recent record-setting years may be "common" in the next few decades (*high confidence*). Much larger rises are projected by late century (2071–2100): 2.8°–7.3°F (1.6°–4.1°C) in a lower scenario (RCP4.5) and 5.8°–11.9°F (3.2°–6.6°C) in a higher scenario (RCP8.5) (*high confidence*).

Description of Evidence Base

The key finding and supporting text summarize extensive evidence documented in the climate science literature. Similar statements about changes have also been made in other reports (e.g., NCA3;[46] Global Climate Change Impacts in the United States[47]). The basic physics underlying the impact of human emissions on climate has also been documented in every IPCC assessment.

Projections are based on global model results and associated downscaled products from CMIP5 for RCP4.5 (lower scenario) and RCP8.5 (higher scenario). Model weighting is employed to refine projections for each RCP. Weighting parameters are based on model independence and skill over North America for seasonal temperature and annual extremes. The multimodel mean is based on 32 model projections that were statistically downscaled using the Localized Constructed Analogs technique.[51] The range is defined as the difference between the average increase in the three coolest models and the average increase in the three warmest models. All increases are significant (i.e., more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change[45]).

Major Uncertainties

Global climate models are subject to structural and parametric uncertainty, resulting in a range of estimates of future changes in average temperature. This is partially mitigated through the use of model weighting and pattern scaling. Furthermore, virtually every ensemble member of every model projection contains an increase in temperature by mid- and late-century. Empirical downscaling introduces additional uncertainty (e.g., with respect to stationarity).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Very high for projected change in annual average temperature; *high confidence* for record-setting years becoming the norm in the near future; *high confidence* for much larger temperature increases by late century under a higher scenario (RCP8.5).

Likelihood of Impact

Extremely likely

Summary sentence or paragraph that integrates the above information

There is *very high confidence* in projected changes in average temperature over the United States based upon the convergence of evidence from multiple model simulations, analyses, and assessments.

Key Finding 4

Extreme temperatures in the contiguous United States are projected to increase even more than average temperatures. The temperatures of extremely cold days and extremely warm days are both expected to increase. Cold waves are projected to become less intense while heat waves will become more intense. The number of days below freezing is projected to decline while the number above 90°F will rise. (*Very high confidence*)

Description of Evidence Base

The key finding and supporting text summarize extensive evidence documented in the climate science literature (e.g., Fischer et al. 2013;[42] Sillmann et al. 2013;[43] Wuebbles et al. 2014;[44] Sun et al. 2015[45]). Similar statements about changes have also been made in other national assessments (such as NCA3) and in reports by the Climate Change Science Program (such as SAP 3.3: Weather and Climate Extremes in a Changing Climate[49]).

Projections are based on global model results and associated downscaled products from CMIP5 for RCP4.5 (lower scenario) and RCP8.5 (higher scenario). Model weighting is employed to refine projections for each RCP. Weighting parameters are based on model independence and skill over North America for seasonal temperature and annual extremes. The multimodel mean is based on 32 model projections that were statistically downscaled using the Localized Constructed Analogs technique.[51] Downscaling improves on the coarse model output, establishing a more geographically accurate baseline for changes in extremes and the number of days per year over key thresholds. The upper bound for projected changes is the average of the three warmest models. All increases are significant (i.e., more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change[45]).

Major Uncertainties

Global climate models are subject to structural and parametric uncertainty, resulting in a range of estimates of future changes in temperature extremes. This is partially mitigated through the use of model weighting and pattern scaling. Furthermore, virtually every ensemble member of every model projection contains an increase in temperature by mid- and late-century. Empirical downscaling introduces additional uncertainty (e.g., with respect to stationarity).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Very high

Likelihood of Impact

Extremely likely

Summary Sentence

There is *very high confidence* in projected changes in temperature extremes over the United States based upon the convergence of evidence from multiple model simulations, analyses, and assessments.

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