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Regional Climate Trends and Scenarios for the U.S. National Climate Assessment

Part 9. Climate of the Contiguous United States

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NOAA Technical Report NESDIS 142-9

Regional Climate Trends and Scenarios for the U.S. National Climate Assessment

Part 9. Climate of the Contiguous United States

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PREFACE

This document is one of series of regional climate descriptions designed to provide input that can be used in the development of the National Climate Assessment (NCA). As part of a sustained assessment approach, it is intended that these documents will be updated as new and well-vetted model results are available and as new climate scenario needs become clear. It is also hoped that these documents (and associated data and resources) are of direct benefit to decision makers and communities seeking to use this information in developing adaptation plans.

There are nine reports in this series, one each for eight regions defined by the NCA, and one for the contiguous U.S. The eight NCA regions are the Northeast, Southeast, Midwest, Great Plains, Northwest, Southwest, Alaska, and Hawaiʻi/Pacific Islands.

These documents include a description of the observed historical climate conditions for each region and a set of climate scenarios as plausible futures – these components are described in more detail below.

While the datasets and simulations in these regional climate documents are not, by themselves, new, (they have been previously published in various sources), these documents represent a more complete and targeted synthesis of historical and plausible future climate conditions around the specific regions of the NCA.

There are two components of these descriptions. One component is a description of the historical climate conditions in the region. The other component is a description of the climate conditions associated with two future pathways of greenhouse gas emissions.

Historical Climate

The description of the historical climate conditions was based on an analysis of core climate data (the data sources are available and described in each document). However, to help understand, prioritize, and describe the importance and significance of different climate conditions, additional input was derived from climate experts in each region, some of whom are authors on these reports. In particular, input was sought from the NOAA Regional Climate Centers and from the American Association of State Climatologists. The historical climate conditions are meant to provide a perspective on what has been happening in each region and what types of extreme events have historically been noteworthy, to provide a context for assessment of future impacts.

Future Scenarios

The future climate scenarios are intended to provide an internally consistent set of climate conditions that can serve as inputs to analyses of potential impacts of climate change. The scenarios are not intended as projections as there are no established probabilities for their future realization. They simply represent an internally consistent climate picture using certain assumptions about the future pathway of greenhouse gas emissions. By “consistent” we mean that the relationships among different climate variables and the spatial patterns of these variables are derived directly from the same set of climate model simulations and are therefore physically plausible.

These future climate scenarios are based on well-established sources of information. No new climate model simulations or downscaled data sets were produced for use in these regional climate reports.

The use of the climate scenario information should take into account the following considerations:

1. All of the maps of climate variables contain information related to statistical significance of changes and model agreement. This information is crucial to appropriate application of the information. Three types of conditions are illustrated in these maps:
    a. The first condition is where most or all of the models simulate statistically significant changes and agree on the direction (whether increasing or decreasing) of the change. If this condition is present, then analyses of future impacts and vulnerabilities can more confidently incorporate this direction of change. It should be noted that the models may still produce a significant range of magnitude associated with the change, so the manner of incorporating these results into decision models will still depend to a large degree on the risk tolerance of the impacted system.
    b. The second condition is where the most or all of the models simulate changes that are too small to be statistically significant. If this condition is present, then assessment of impacts should be conducted on the basis that the future conditions could represent a small change from present or could be similar to current conditions and that the normal year-to-year fluctuations in climate dominate over any underlying long-term changes.
    c. The third condition is where most or all of the models simulate statistically significant changes but do not agree on the direction of the change, i.e. a sizeable fraction of the models simulate increases while another sizeable fraction simulate decreases. If this condition is present, there is little basis for a definitive assessment of impacts, and, separate assessments of potential impacts under an increasing scenario and under a decreasing scenario would be most prudent.
2. The range of conditions produced in climate model simulations is quite large. Several figures and tables provide quantification for this range. Impacts assessments should consider not only the mean changes, but also the range of these changes.
3. Several graphics compare historical observed mean temperature and total precipitation with model simulations for the same historical period. These should be examined since they provide one basis for assessing confidence in the model simulated future changes in climate.
    a. Temperature Changes: Magnitude. In most regions, the model simulations of the past century simulate the magnitude of change in temperature from observations; the southeast region being an exception where the lack of century-scale observed warming is not simulated in any model.
    b. Temperature Changes: Rate. The *rate* of warming over the last 40 years is well simulated in all regions.
    c. Precipitation Changes: Magnitude. Model simulations of precipitation generally simulate the overall observed trend but the observed decade-to-decade variations are greater than the model observations.

In general, for impacts assessments, this information suggests that the model simulations of temperature conditions for these scenarios are likely reliable, but users of precipitation simulations may want to consider the likelihood of decadal-scale variations larger than simulated by the models. It should also be noted that accompanying these documents will be a web-based resource with downloadable graphics, metadata about each, and more information and links to the datasets and overall descriptions of the process.

1. INTRODUCTION

The Global Change Research Act of 1990[1] mandated that national assessments of climate change be prepared not less frequently than every four years. The last national assessment was published in 2009 (Karl et al. 2009). To meet the requirements of the act, the Third National Climate Assessment (NCA) report is now being prepared. The National Climate Assessment Development and Advisory Committee (NCADAC), a federal advisory committee established in the spring of 2011, will produce the report. The NCADAC Scenarios Working Group (SWG) developed a set of specifications with regard to scenarios to provide a uniform framework for the chapter authors of the NCA report.

This climate document was prepared to provide a resource for authors of the Third National Climate Assessment report, pertinent to the 48 contiguous United States. The specifications of the NCADAC SWG, along with anticipated needs for historical information, guided the choices of information included in this description of U.S. climate. While guided by these specifications, the material herein is solely the responsibility of the authors and usage of this material is at the discretion of the 2013 NCA report authors.

This document has two main sections: one on historical conditions and trends, and the other on future conditions as simulated by climate models. The historical section concentrates on temperature and precipitation, primarily based on analyses of data from the National Weather Service's (NWS) Cooperative Observer Network, which has been in operation since the late 19th century. Additional climate features are discussed based on the availability of information. The future simulations section is exclusively focused on temperature and precipitation.

With regard to the future, the NCADAC, at its May 20, 2011 meeting, decided that scenarios should be prepared to provide an overall context for assessment of impacts, adaptation, and mitigation, and to coordinate any additional modeling used in synthesizing or analyzing the literature. Scenario information for climate, sea-level change, changes in other environmental factors (such as land cover), and changes in socioeconomic conditions (such as population growth and migration) have been prepared. This document provides an overall description of the climate information.

In order to complete this document in time for use by the NCA report authors, it was necessary to restrict its scope in the following ways. Firstly, this document does not include a comprehensive description of all climate aspects of relevance and interest to a national assessment. We restricted our discussion to climate conditions for which data were readily available. Secondly, the choice of climate model simulations was also restricted to readily available sources. Lastly, the document does not provide a comprehensive analysis of climate model performance for historical climate conditions, although a few selected analyses are included.

The NCADAC directed the "use of simulations forced by the A2 emissions scenario as the primary basis for the high climate future and by the B1 emissions scenario as the primary basis for the low climate future for the 2013 report" for climate scenarios. These emissions scenarios were generated by the Intergovernmental Panel on Climate Change (IPCC) and are described in the IPCC Special Report on Emissions Scenarios (SRES) (IPCC 2000). These scenarios were selected because they incorporate much of the range of potential future human impacts on the climate system and because

[1] http://thomas.loc.gov/cgi-bin/bdquery/z?d101:SN00169:|TOM:/bss/d101query.html

there is a large body of literature that uses climate and other scenarios based on them to evaluate potential impacts and adaptation options. These scenarios represent different narrative storylines about possible future social, economic, technological, and demographic developments. These SRES scenarios have internally consistent relationships that were used to describe future pathways of greenhouse gas emissions. The A2 scenario "describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in the other storylines" (IPCC 2000). The B1 scenario describes "a convergent world with…global population that peaks in mid-century and declines thereafter…but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives" (IPCC 2000).

The temporal changes of emissions under these two scenarios are illustrated in Fig. 1 (left panel). Emissions under the A2 scenario continually rise during the 21st century from about 40 gigatons (Gt) CO_2-equivalent per year in the year 2000 to about 140 Gt CO_2-equivalent per year by 2100. By contrast, under the B1 scenario, emissions rise from about 40 Gt CO_2-equivalent per year in the year 2000 to a maximum of slightly more than 50 Gt CO_2-equivalent per year by mid-century, then falling to less than 30 Gt CO_2-equivalent per year by 2100. Under both scenarios, CO_2 concentrations rise throughout the 21st century. However, under the A2 scenario, there is an acceleration in concentration trends, and by 2100 the estimated concentration is above 800 ppm. Under the B1 scenario, the rate of increase gradually slows and concentrations level off at about 500 ppm by 2100. An increase of 1 ppm is equivalent to about 8 Gt of CO_2. The increase in concentration is considerably smaller than the rate of emissions because a sizeable fraction of the emitted CO_2 is absorbed by the oceans.

The projected CO_2 concentrations are used to estimate the effects on the earth's radiative energy budget, and this is the key forcing input used in global climate model simulations of the future. These simulations provide the primary source of information about how the future climate could evolve in response to the changing composition of the earth's atmosphere. A large number of modeling groups performed simulations of the 21st century in support of the IPCC's Fourth Assessment Report (AR4), using these two scenarios. The associated changes in global mean temperature by the year 2100 (relative to the average temperature during the late 20th century) are about +6.5°F (3.6°C) under the A2 scenario and +3.2°F (1.8°C) under the B1 scenario with considerable variations among models (Fig. 1, right panel).

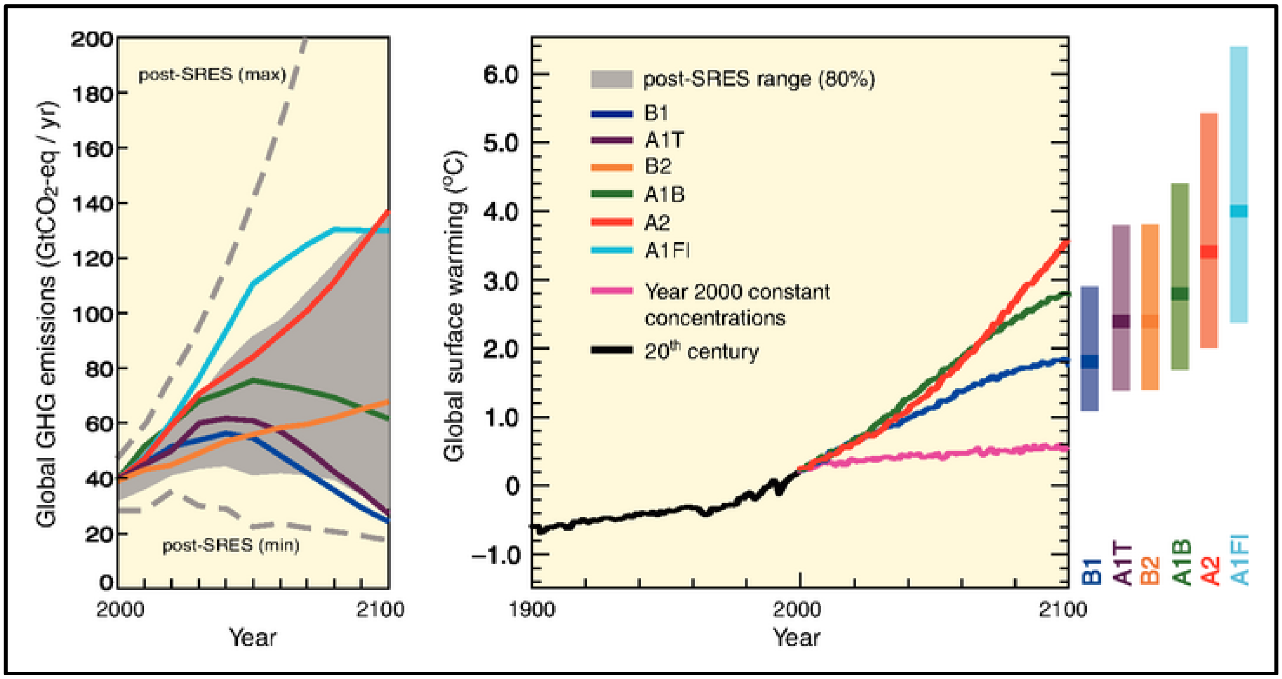

Figure 1. Left Panel: Global GHG emissions (in $GtCO_2$-eq) in the absence of climate policies: six illustrative SRES marker scenarios (colored lines) and the 80th percentile range of recent scenarios published since SRES (post-SRES) (gray shaded area). Dashed lines show the full range of post-SRES scenarios. The emissions include CO_2, CH_4, N_2O and F-gases. Right Panel: Solid lines are multi-model global averages of surface warming for scenarios A2, A1B and B1, shown as continuations of the 20th-century simulations. These projections also take into account emissions of short-lived GHGs and aerosols. The pink line is not a scenario, but is for Atmosphere-Ocean General Circulation Model (AOGCM) simulations where atmospheric concentrations are held constant at year 2000 values. The bars at the right of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090-2099. All temperatures are relative to the period 1980-1999. From IPCC AR4, Sections 3.1 and 3.2, Figures 3.1 and 3.2, IPCC (2007b).

In addition to the direct output of the global climate model simulations, the NCADAC approved "the use of both statistically- and dynamically-downscaled data sets". "Downscaling" refers to the process of producing higher-resolution simulations of climate from the low-resolution outputs of the global models. The motivation for use of these types of data sets is the spatial resolution of global climate models. While the spatial resolution of available global climate model simulations varies widely, many models have resolutions in the range of 100-200 km (~60-120 miles). Such scales are very large compared to local and regional features important to many applications. For example, at these scales mountain ranges are not resolved sufficiently to provide a reasonably accurate representation of the sharp gradients in temperature, precipitation, and wind that typically exist in these areas.

Statistical downscaling achieves higher-resolution simulations through the development of statistical relationships between large-scale atmospheric features that are well-resolved by global models and the local climate conditions that are not well-resolved. The statistical relationships are developed by comparing observed local climate data with model simulations of the recent historical climate. These relationships are then applied to the simulations of the future to obtain local high-resolution projections. Statistical downscaling approaches are relatively economical from a computational perspective, and thus they can be easily applied to many global climate model simulations. One underlying assumption is that the relationships between large-scale features and local climate conditions in the present climate will not change in the future (Wilby and Wigley 1997). Careful consideration must also be given when deciding how to choose the appropriate predictors because statistical downscaling is extremely sensitive to the choice of predictors (Norton et al. 2011).

Dynamical downscaling is much more computationally intensive but avoids assumptions about constant relationships between present and future. Dynamical downscaling uses a climate model, similar in most respects to the global climate models. However, the climate model is run at a much higher resolution but only for a small region of the earth (such as North America) and is termed a "regional climate model (RCM)". A global climate model simulation is needed to provide the boundary conditions (e.g., temperature, wind, pressure, and humidity) on the lateral boundaries of the region. Typically, the spatial resolution of an RCM is 3 or more times higher than the global model used to provide the boundary conditions. With this higher resolution, topographic features and smaller-scale weather phenomena are better represented. The major downside of dynamical downscaling is that a simulation for a region can take as much computer time as a global climate model simulation for the entire globe. As a result, the availability of such simulations is limited, both in terms of global models used for boundary conditions and time periods of the simulations (Hayhoe 2010).

Section 3 of this document (Future National Climate Scenarios) responds to the NCADAC directives by incorporating analyses from multiple sources. The core source is the set of global climate model simulations performed for the IPCC AR4, also referred to as the Climate Model Intercomparison Project phase 3 (CMIP3) suite. These have undergone extensive evaluation and analysis by many research groups. A second source is a set of statistically-downscaled data sets based on the CMIP3 simulations. A third source is a set of dynamically-downscaled simulations, driven by CMIP3 models. A new set of global climate model simulations is being generated for the IPCC Fifth Assessment Report (AR5). This new set of simulations is referred to as the Climate Model Intercomparison Project phase 5 (CMIP5). These scenarios do not incorporate any CMIP5 simulations as relatively few were available at the time the data analyses were initiated.
As noted earlier, the information included in this document is primarily concentrated around analyses of temperature and precipitation. This is explicitly the case for the future scenarios sections; due in large part to the short time frame and limited resources, we capitalized on the work of other groups on future climate simulations, and these groups have devoted a greater effort to the analysis of temperature and precipitation than other surface climate variables.

Climate models have generally exhibited a high level of ability to simulate the large-scale circulation patterns of the atmosphere. These include the seasonal progression of the position of the jet stream and associated storm tracks, the overall patterns of temperature and precipitation, the occasional occurrence of droughts and extreme temperature events, and the influence of geography on climatic patterns. There are also important processes that are less successfully simulated by models, as noted by the following selected examples.

Climate model simulation of clouds is problematic. Probably the greatest uncertainty in model simulations arises from clouds and their interactions with radiative energy fluxes (Dufresne and Bony 2008). Uncertainties related to clouds are largely responsible for the substantial range of global temperature change in response to specified greenhouse gas forcing (Randall et al. 2007). Climate model simulation of precipitation shows considerable sensitivities to cloud parameterization schemes (Arakawa 2004). Cloud parameterizations remain inadequate in current GCMs. Consequently, climate models have large biases in simulating precipitation, particularly in the tropics. Models typically simulate too much light precipitation and too little heavy precipitation in both the tropics and middle latitudes, creating potential biases when studying extreme events (Bader et al. 2008).

Climate models also have biases in simulation of some important climate modes of variability. The El Niño-Southern Oscillation (ENSO) is a prominent example. In some parts of the U.S., El Niño and La Niña events make important contributions to year-to-year variations in conditions. Climate models have difficulty capturing the correct phase locking between the annual cycle and ENSO (AchutaRao and Sperber 2002). Some climate models also fail to represent the spatial and temporal structure of the El Niño - La Niña asymmetry (Monahan and Dai 2004). Climate simulations over the U.S. are affected adversely by these deficiencies in ENSO simulations.

The model biases listed above add additional layers of uncertainty to the information presented herein and should be kept in mind when using the climate information in this document.

The representation of the results of the suite of climate model simulations has been a subject of active discussion in the scientific literature. In many recent assessments, including AR4, the results of climate model simulations have been shown as multi-model mean maps (e.g., Figs. 10.8 and 10.9 in Meehl et al. 2007). Such maps give equal weight to all models, which is thought to better represent the present-day climate than any single model (Overland et al. 2011). However, models do not represent the current climate with equal fidelity. Knutti (2010) raises several issues about the multi-model mean approach. These include: (a) some model parameterizations may be tuned to observations, which reduces the spread of the results and may lead to underestimation of the true uncertainty; (b) many models share code and expertise and thus are not independent, leading to a reduction in the true number of independent simulations of the future climate; (c) all models have some processes that are not accurately simulated, and thus a greater number of models does not necessarily lead to a better projection of the future; and (d) there is no consensus on how to define a metric of model fidelity, and this is likely to depend on the application. Despite these issues, there is no clear superior alternative to the multi-model mean map presentation for general use. Tebaldi et al. (2011) propose a method for incorporating information about model variability and consensus. This method is adopted here where data availability make it possible. In this method, multi-model mean values at a grid point are put into one of three categories: (1) models agree on the statistical significance of changes and the sign of the changes; (2) models agree that the changes are not statistically significant; and (3) models agree that the changes are statistically significant but disagree on the sign of the changes. The details on specifying the categories are included in Section 3.

2. NATIONAL CLIMATE TRENDS AND IMPORTANT CLIMATE FACTORS

2.1. Description of Data Sources

One of the core data sets used in the United States for climate analysis is the National Weather Service's Cooperative Observer Network (COOP), which has been in operation since the late 19th century. The resulting data can be used to examine long-term trends. The typical COOP observer takes daily observations of various climate elements that might include precipitation, maximum temperature, minimum temperature, snowfall, and snow depth. While most observers are volunteers, standard equipment is provided by the National Weather Service (NWS), as well as training in standard observational practices. Diligent efforts are made by the NWS to find replacement volunteers when needed to ensure the continuity of stations whenever possible. Over a thousand of these stations have been operation continuously for many decades (NOAA 2012a).

For examination of U.S. long-term trends in temperature and precipitation, the COOP data is the best available resource. Its central purpose is climate description (although it has many other applications as well); the number of stations is large, there have been relatively few changes in instrumentation and procedures, and it has been in existence for over 100 years. However, there are some sources of temporal inhomogeneities in station records, described as follows:

- One instrumental change is important. For much of the COOP history, the standard temperature system was a pair of liquid-in-glass (LIG) thermometers placed in a radiation shield known as the Cotton Region Shelter (CRS). In the 1980s, the NWS began replacing this system with an electronic maximum-minimum temperature system (MMTS). Inter-comparison experiments indicated that there is a systematic difference between these two instrument systems, with the newer electronic system recording lower daily maximum temperatures (T_{max}) and higher daily minimum temperatures (T_{min}) (Quayle et al. 1991; Hubbard and Lin 2006; Menne et al. 2009). Menne et al. (2009) estimate that the mean shift (going from CRS/LIG to MMTS) is -0.52K for T_{max} and +0.37K for T_{min}. Adjustments for these differences can be applied to monthly mean temperature to create homogeneous time series.
- Changes in the characteristics and/or locations of sites can introduce artificial shifts or trends in the data. In the COOP network, a station is generally not given a new name or identifier unless it moves at least 5 miles and/or changes elevation by at least 100 feet (NWS 1993). Site characteristics can change over time and affect a station's record, even if no move is involved (and even small moves << 5 miles can have substantial impacts). A common source of such changes is urbanization around the station, which will generally cause artificial warming, primarily in T_{min} (Karl et al. 1988), the magnitude of which can be several degrees in the largest urban areas. Most research suggests that the overall effect on national and global temperature trends is rather small because of the large number of rural stations included in such analyses (Karl et al. 1988; Jones et al. 1990) and because homogenization procedures reduce the urban signal (Menne et al. 2009).
- Station siting can cause biases. Recent research by Menne et al. (2010) and Fall et al. (2011) examined this issue in great detail. The effects on mean trends was found to be small in both studies, but Fall et al. (2011) found that stations with poor siting overestimate (underestimate) minimum (maximum) temperature trends.

- Changes in the time that observations are taken can also introduce artificial shifts or trends in the data (Karl et al. 1986; Vose et al. 2003). In the COOP network, typical observation times are early morning or late afternoon, near the usual times of the daily minimum and maximum temperatures. Because observations occur near the times of the daily extremes, a change in observation time can have a measurable effect on averages, irrespective of real changes. The study by Karl et al. (1986) indicates that the difference in monthly mean temperatures between early morning and late afternoon observers can be in excess of 2°C. There has, in fact, been a major shift from a preponderance of afternoon observers in the early and middle part of the 20th century to a preponderance of morning observers at the present time. In the 1930s, nearly 80% of the COOP stations were afternoon observers (Karl et al. 1986). By the early 2000s, the number of early morning observers was more than double the number of late afternoon observers (Menne et al. 2009). This shift tends to introduce an artificial cooling trend in the data.

A recent study by Williams et al. (2011) found that correction of known and estimated inhomogeneities lead to a larger warming trend in average temperature, principally arising from correction of the biases introduced by the changeover to the MMTS and from the biases introduced by the shift from mostly afternoon observers to mostly morning observers.

Much of the following analysis on temperature, precipitation, and snow is based on COOP data. For some of these analyses, a subset of COOP stations with long periods of record was used, specifically less than 10% missing data for the period of 1895-2011. The use of a consistent network is important when examining trends in order to minimize artificial shifts arising from a changing mix of stations.

2.2. General Description of United States Climate

The contiguous United States is characterized by a highly diverse climate with large spatial variations. The great latitudinal range of this region leads to a very wide range in temperatures. In addition to the latitudinal range, several geographic factors contribute to this variability. The mountains in the west of the region lead directly to spatial variations through the elevation dependence of temperature and through precipitation caused by forced ascent of air. In addition, these mountains inhibit and block the movement of air masses. Moist Pacific air masses moving to the east lose much of their moisture as they pass over the mountains, leading to generally arid conditions in the interior west. They also limit the westward penetration of humid air masses from the Gulf of Mexico. Cold (and dense) air masses moving southward from the Arctic and interior Canada are inhibited from moving westward by the mountain barriers. By contrast, the lack of high mountains to the north and south of the interior central and eastern U.S. means that those regions are exposed to outbreaks of Arctic air which can bring bitter cold during the winter and to warm, and humid air masses that circulate around a semi-permanent high pressure system in the subtropical Atlantic.

The polar jet stream is often located near or over northern and central regions (and sometimes over the south) during the winter, bringing storm systems that create cloudy skies, windy conditions, and precipitation. Potentially dangerous storms occur in every season. Winter can bring major snowstorms, damaging ice storms, or both. Warmer months, typically March-October, have heat waves and convective storms, including thunderstorms and lightning, flood-producing rainstorms, hail, and deadly tornadoes. Hurricanes are a major weather phenomenon for the Gulf and Atlantic coastal areas.

The range of annual average temperature is very large (Fig. 2). The coldest temperatures of less than 40°F occur in the higher mountain areas and along the northern border with Canada. By contrast, the average annual temperatures are greater than 70°F in the desert southwest, south Texas, and south Florida.

Average annual precipitation (Fig. 3) also exhibits an extremely large range, illustrating the particular geographic features that determine the frequency of high moisture transport from oceanic sources. Much of the western U.S. receives less than 15 inches annually, except for higher mountain areas and the northern coastal regions. Much of the eastern U.S. receives more than 40 inches. The Great Plains is a transition zone between the mostly arid and semi-arid regions of the west and the humid regions of the east.

The major urban centers experience the typical types of sensitivities that are unique to, or exacerbated by, the specific characteristics of the urban environment. Temperature extremes can have large impacts on human health, particularly in the urban core where the urban heat island effect raises summer temperatures. Severe storms, both winter and summer, result in major disruptions to surface and air transportation. Extreme rainfall causes a host of problems, including storm sewer overflow, flooding of homes and roadways, and contamination of municipal water supplies. Climate extremes combined with the urban pollution sources can create air quality conditions that are detrimental to human health.

2.3. Important Climate Factors

The United States experiences a wide range of extreme weather and climate events that affect human society, ecosystems, and infrastructure. This discussion is meant to provide general information about these types of weather and climate phenomena.

Figure 4 shows a time series of the number of climate extreme events causing at least $1 billion in damages. There has been at least 1 such event each year since 1988 and the preliminary total for 2011 is the highest of the entire period. The observed temporal changes in losses represent a combination of the effects of both physical climate and socio-economic variability (e.g., Pielke et al. 2008), and it is difficult to attribute any of the trends solely to climate (Bouwer 2011).

The locations, types, and dollar losses for individual events are shown in Fig. 5. Such events have occurred throughout the U.S., although there are relatively few in the less populated regions of the northern Plains and intermountain west. Many different weather and climate phenomena are represented in this summary of disasters, and these are individually described below.

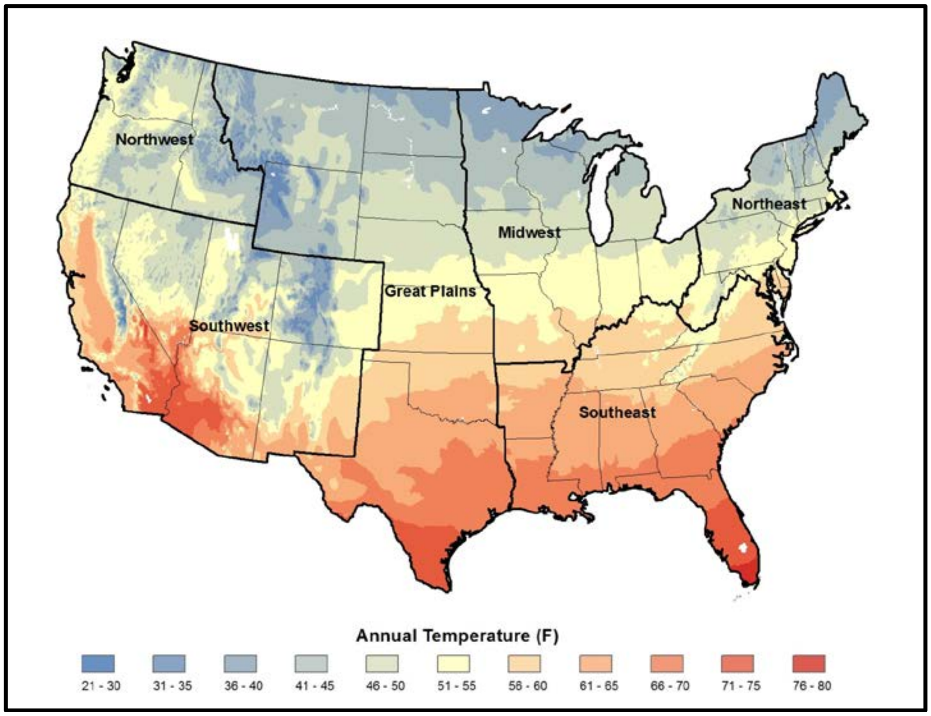

Figure 2. Average (1981-2010) annual temperature (°F) for the contiguous United States. Based on a new gridded version of COOP data from the National Climatic Data Center, the CDDv2 data set (R. Vose, personal communication, July 27, 2012).

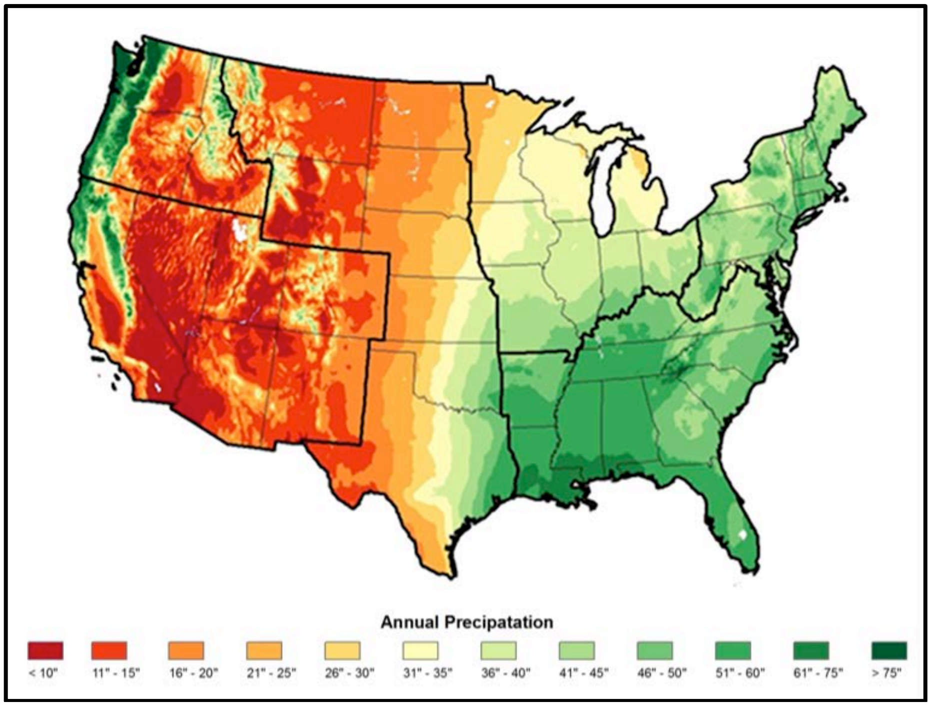

Figure 3. Average (1981-2010) annual precipitation (inches) for the contiguous United States. Based on a new gridded version of COOP data from the National Climatic Data Center, the CDDv2 data set (R. Vose, personal communication, July 27, 2012).

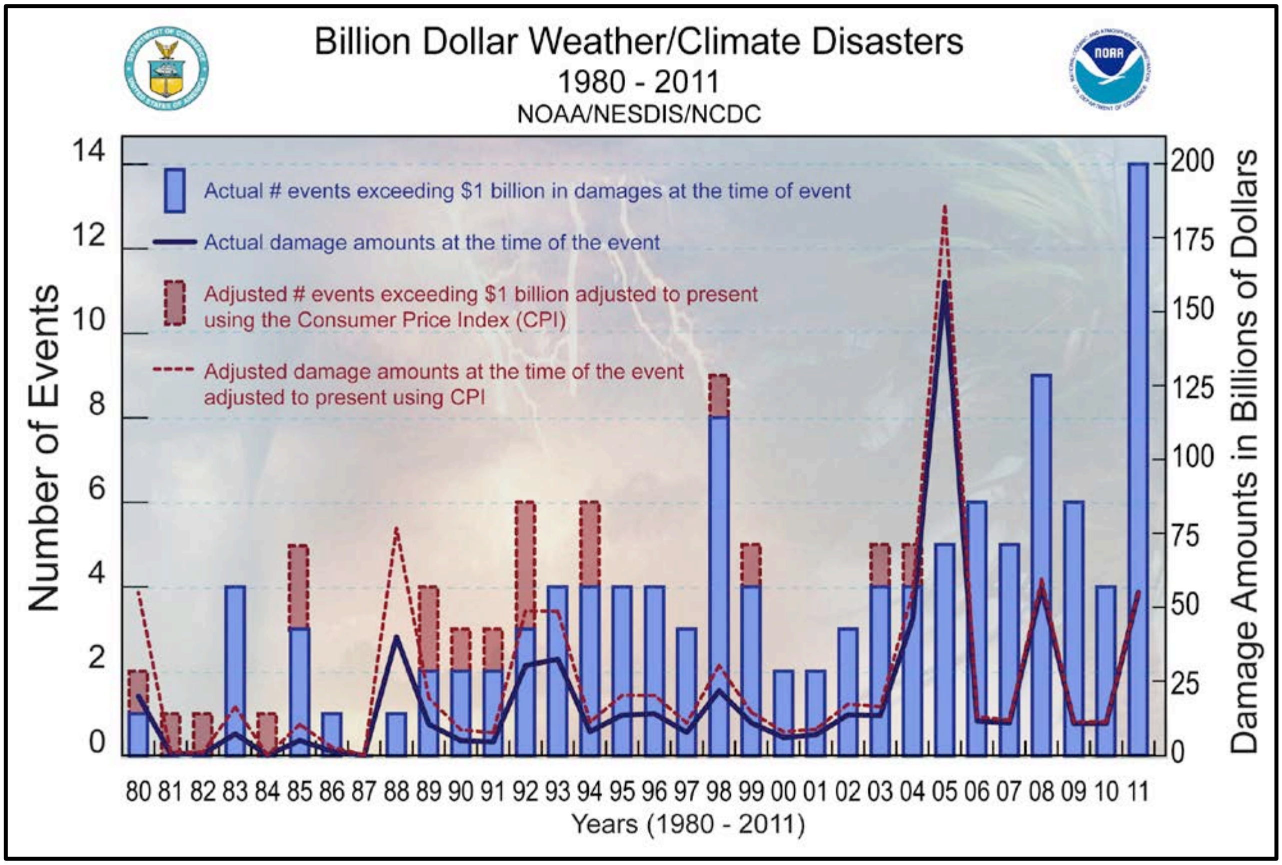

Figure 4. Annual number of weather events causing at least $1 billion in losses in the United States (NOAA 2011a). Data from NOAA's National Climatic Data Center (NCDC).

2.3.1. Drought

Various types of drought can occur throughout the nation. For example, *meteorological drought* (defined solely by the severity and duration of a dry period) occurs in some portion of the U.S. nearly every year. Other types of drought are measured by the dryness relative to the needs for water in various sectors. *Agricultural drought* largely refers to climate related problems in food production for farmers and cattlemen; its occurrence is highly dependent on the timing of the dry period. *Hydrological drought* occurs when water supply is reduced due to periods of precipitation shortages. The hydrologic storage systems are negatively impacted, with less water available for irrigation, navigation, hydropower and recreation.

Drought can occur in any area. The Dust Bowl is by far the most famous drought over the past 100 years, but prolonged drought has occurred recently as well. Record-setting drought and heat affected Texas and surrounding areas in 2011 and much of the country in 2012 (Karl et al. 2012).

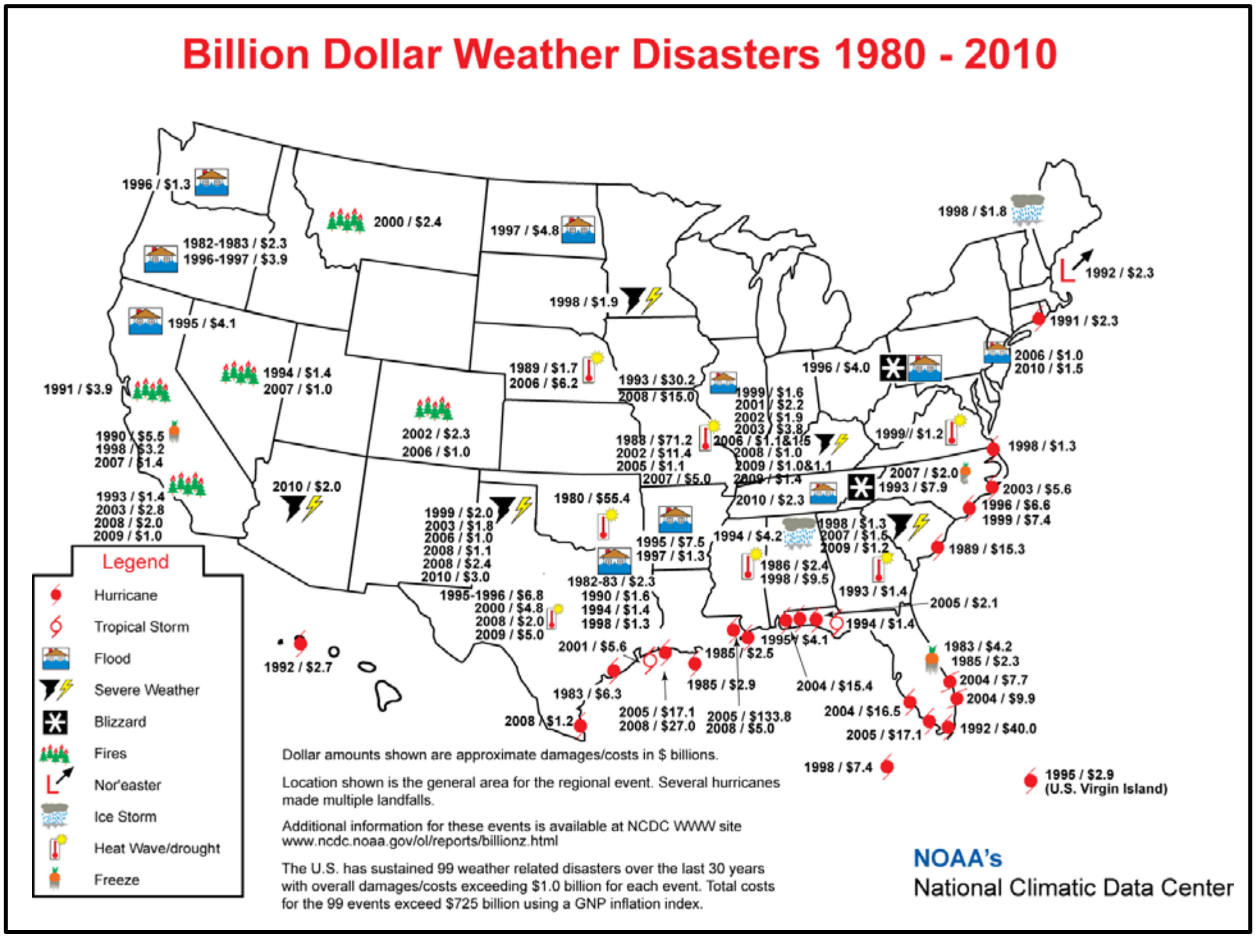

Figure 5. Information on each of the billion dollar disasters represented in Fig. 4, including the location, year, dollar loss (in billions), and the type. Data from NOAA's National Climatic Data Center (NCDC).

2.3.2. Floods

Floods can be categorized into several types. One occurs when melting of a heavy snow pack in the mountains leads to flooding of rivers downstream and dangerously full reservoirs. For instance, floods in the Red River basin occur primarily during April and May and are caused by rapid spring snowmelt that may be accompanied by rain. A second type of flood is associated with short-duration heavy rainfall, usually from summer convection. Such meteorological events can cause flooding on small to medium size streams. A third type is prolonged (days to weeks) heavy rainfall over large areas. This type of situation can cause severe flooding on the largest rivers. The severe flooding during 1993 and 2011 in the Mississippi River basin resulted from weeks of heavy precipitation.

2.3.3. Winter Storms

The U.S. is highly susceptible to the impacts of winter storm systems, which can produce heavy snows, high winds with blowing snow and reduced visibility, low wind chill temperatures and can establish the conditions for snowmelt flooding. Major impacts primarily include a disruption of transportation and commerce, high removal costs, and loss of life and livestock due to exposure. For the southern U.S., severe winter storms are less common whereas ice storm events are generally more frequent than in the north (Changnon et al. 2006). Historically speaking, winter storms exhibit high variability in frequency of occurrence over time.

Snow represents an important natural resource and is a significant component of the climate system with the ability to modify the surface energy budget. Snowfall represents one of the most difficult meteorological variables to accurately measure. However, high quality surface observing stations in the region show trends in seasonal snowfall amounts over time. Since the 1920s, snowfall has been declining in the West and along the Mid-Atlantic Coast. In some places during recent years the decline has been more precipitous, strongly trending downward along the southern margins of the seasonal snow region, the southern Missouri River basin, and parts of the Northeast. Snowfall has been increasing since the 1920s in the lee of the Rocky Mountains, the Great Lakes – northern Ohio Valley, and parts of the north-central U.S. (Kunkel et al. 2009). Little trend has been observed in the Sierra Nevada Mountains (Christy 2012).

2.3.4. Convective Storms

The U.S. experiences a high frequency of convective storms during the spring and summer months, particularly in the central and eastern U.S. Hazards from these events include downbursts, heavy downpours, and lightning, hail, tornadoes, and flash flooding. Severe storms peak in the spring for the southern U.S. while the peak in storm activity is in summer in the north. The central and southern portion of the Great Plains is often referred to as ‘tornado alley’ due to the frequency of these events here compared to elsewhere in the U.S. (e.g., more than 100 per year on average in Texas and more than 50 per year in Kansas and Oklahoma). However, tornadoes are also frequent in the Midwestern and eastern U.S. The year 2011 was a particularly active one for destructive tornadoes and high loss of life, noteworthy examples being the tornadoes that struck Tuscaloosa, AL and Joplin, MO. Hail events associated with convective storm events peak in the central and southern Great Plains of the U.S. (Changnon et al. 2009). While most hail is too small to cause much damage, some can be quite large and damaging to life and property.

2.3.5. Heat Waves

Heat waves occur throughout the U.S. and affect health and comfort. Some examples of historic heat waves include the Dust Bowl of the 1930s (Schubert et al. 2004), the 1980 summer heat wave and drought (Karl and Quayle 1981), and the 1988 heat wave and drought. Most recently, the heat wave and drought of the summer of 2011 across the southern portions of the central U.S. seriously affected the livelihoods of many people through crop and livestock failures, depletion of water supplies, and more. According to NOAA’s National Climatic Data Center (NCDC), both Texas and Oklahoma recorded their warmest summer on record (records date back to 1895). Most areas of Texas and Oklahoma experienced at least 40 days of 100˚F+ heat (Fig. 6). The summer of 2012 was characterized by extreme heat and drought over large portions of the U.S. For example, July 2012 was the hottest month on record in the U.S., surpassing the old record of July 1936 (Karl et al. 2012).

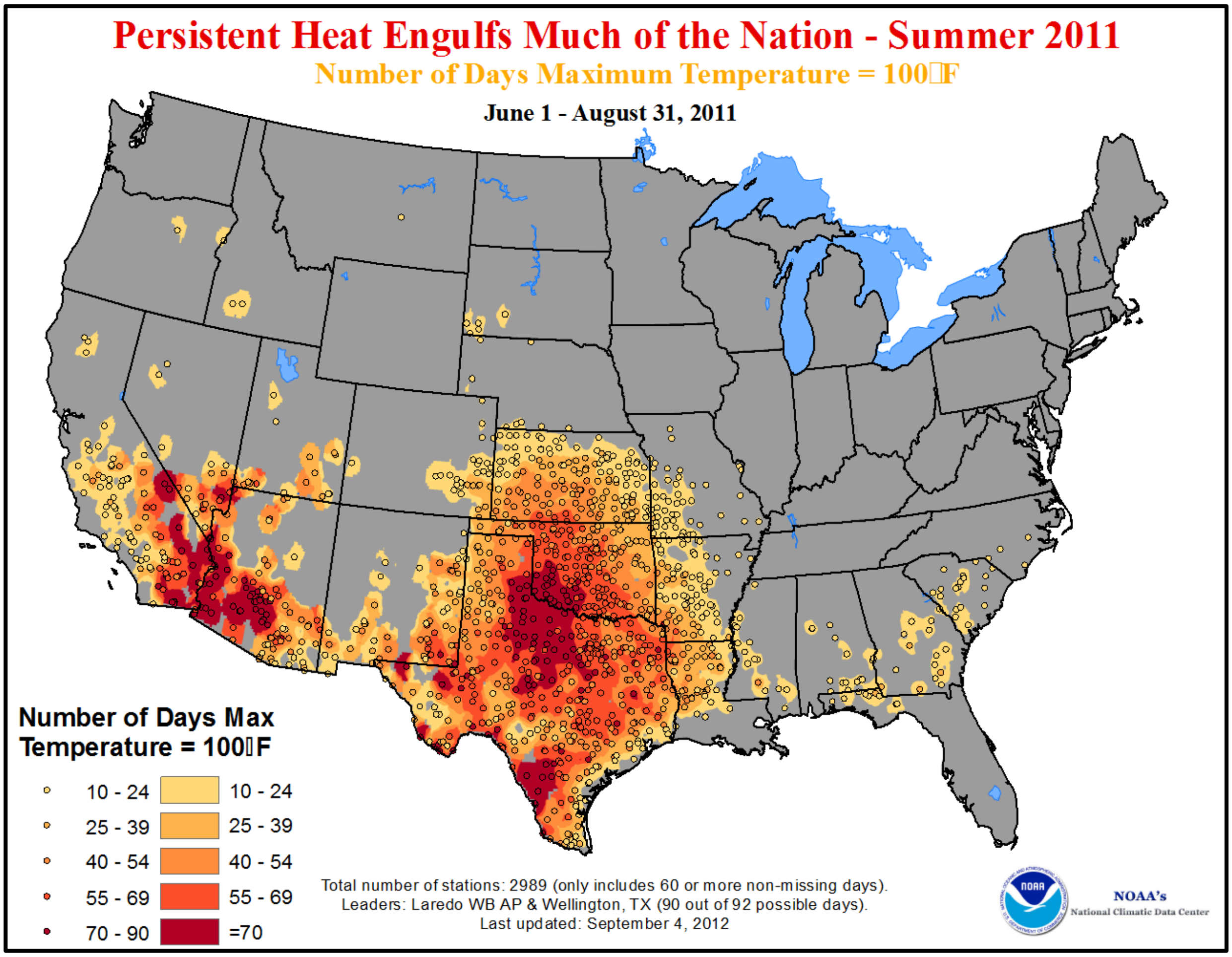

Figure 6. Number of days with maximum temperature exceeding 100˚F in Summer 2011 across the contiguous U.S. (NOAA 2011b). Data from NOAA's National Climatic Data Center (NCDC).

2.3.6. Cold Waves

During most winters arctic air from Canada routinely plunges south into the central and eastern parts of the U.S. The blocking effect of the mountains and the moderating influence of the Pacific Ocean tend to moderate unusual cold in the far western U.S. For example, the record low temperatures at Bismarck, ND and Seattle, WA are -33˚F and +14˚F, respectively, yet these two cities are at similar latitudes.

2.3.7. Hurricanes

Hurricanes are a major weather hazard for coastal regions of the Gulf of Mexico and the Atlantic. The most damaging U.S. weather event of modern times was Hurricane Katrina in 2005 with losses in excess of $100 billion. Fig. 7 shows the number of coastal hurricane strikes since 1900. The largest numbers of strikes have occurred in northeast Texas, southern Louisiana and Mississippi, southeastern Florida, and eastern North Carolina. However, strikes have occurred all along the coastal regions from southern Texas to northern Maine. Time series of the number of U.S. landfalling hurricanes does not indicate any trend over time.

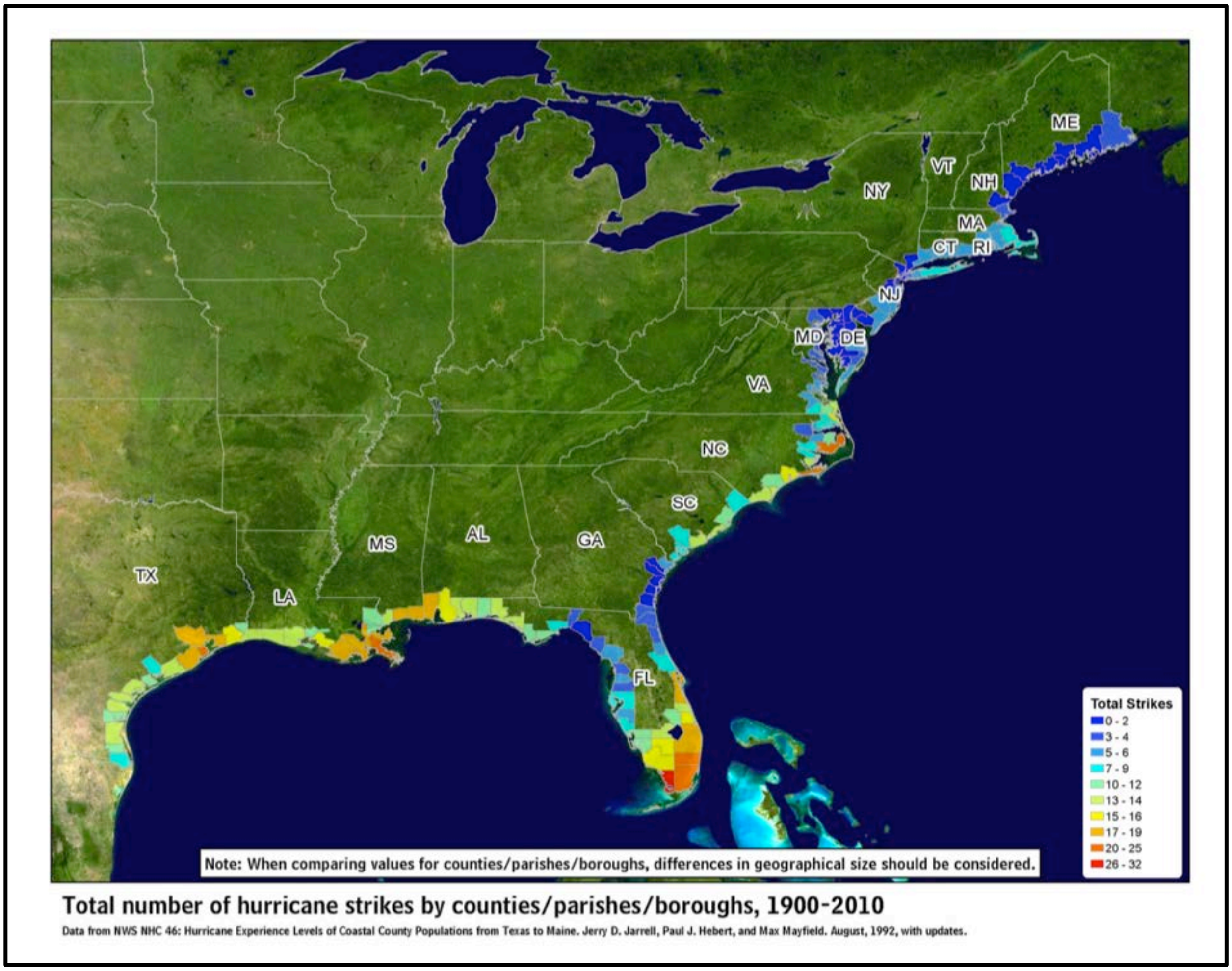

Figure 7. Number of hurricane strikes in coastal regions for the period 1900-2010. Figure courtesy of the National Hurricane Center (NWS 2012), from Jarrell et al. (1992) and updates.

2.4. Climatic Trends

The temperature and precipitation data sets used to examine trends were obtained from NOAA's National Climatic Data Center (NCDC). The NCDC data is based on NWS Cooperative Observer Network (COOP) observations, as descibed in Section 2.1. Some analyses use daily observations for selected stations from the COOP network. Other analyses use a new national gridded monthly data set at a resolution of 5 x 5 km, for the time period of 1895-2011. This gridded data set is derived from bias-corrected monthly station data and is named the "Climate Division Database version 2 beta" (CDDv2) and is scheduled for public release in January 2013 (R. Vose, NCDC, personal communication, July 27, 2012).

The COOP data were processed using 1901-1960 as the reference period to calculate anomalies. There were two considerations in choosing this period. Firstly, while some gradually-increasing anthropogenic forcing was present in the early and middle part of the 20th century, there is a pronounced acceleration of the forcing after 1960 (Meehl et al. 2003). Thus, there is an expectation that the effects of that forcing on surface climate conditions should accelerate after 1960. This year was therefore chosen as the ending year of the reference period. Secondly, in order to average out the natural fluctuations in climate as much as possible, it is desirable to use the longest practical reference period. Both observational and climate model data are generally available starting around the turn of the 20^{th} century, thus motivating the use of 1901 as the beginning year of the reference period. We use this period as the reference for historical time series appearing in this section in order to be consistent with related figures in Section 3.

2.4.1. Temperature

Figure 8 shows annual and seasonal time series of temperature anomalies for the period of 1895-2011. Annual temperatures have been generally (all but 2 years) above the 1901-1960 average for the last 20 years (Fig. 8, top). The warmest years on record were 1998 and 2006 (virtual tie). The heat that occurred during the Dust Bowl era is very evident in the summer time series (Fig. 8, bottom left). The warmest summer on record was 1936, followed closely by 2011. Twelve of the last fourteen summers have been above average. Temperatures during the other seasons (Fig. 8, middle and bottom) have also generally been above average in recent years.

Table 1 shows temperature trends by region for the period of 1895-2011, using the CDDv2 data set. Values are only displayed for trends that are statistically significant at the 95% confidence level. Annual temperature trends are upward with magnitudes varying from 0.09 to 0.20°F/decade. They are statistically significant in all regions except for the Southeast, which is also the case for the spring season. Trends for winter are statistically significant in all regions except the Southeast and Midwest. For the summer, trends are not statistically significant in the Southeast, Midwest, and Great Plains-South. The lack of summer trend in these areas has been dubbed the “warming hole”. Trends are statistically significant for the fall only in the Northeast, Northwest, and Southwest.

Table 1. 1895-2011 trends in temperature anomaly (°F/decade) based on a new gridded version of COOP data from the National Climatic Data Center, the CDDv2 data set (R. Vose, personal communication, July 27, 2012) for the six NCA regions of the continental U.S. (including the northern and southern Great Plains), for each season as well as the year as a whole. Only values statistically significant at the 95% confidence level are displayed. Statistical significance of trends was assessed using Kendall’s tau coefficient. The test using tau is a non-parametric hypothesis test.

Region	**Winter**	**Spring**	**Summer**	**Fall**	**Annual**
Contiguous U.S.	+0.19	+0.13	+0.10	+0.09	+0.13
Northeast	+0.24	+0.14	+0.11	+0.12	+0.16
Southeast	—	—	—	—	—
Midwest	—	+0.17	—	—	+0.14
Great Plains	+0.24	+0.16	+0.09	—	+0.15
North	*+0.33*	*+0.20*	*+0.14*	—	*+0.20*
South	*+0.14*	*+0.11*	—	—	*+0.09*
Northwest	+0.20	—	+0.12	+0.10	+0.10
Southwest	+0.21	+0.16	+0.17	+0.16	+0.17

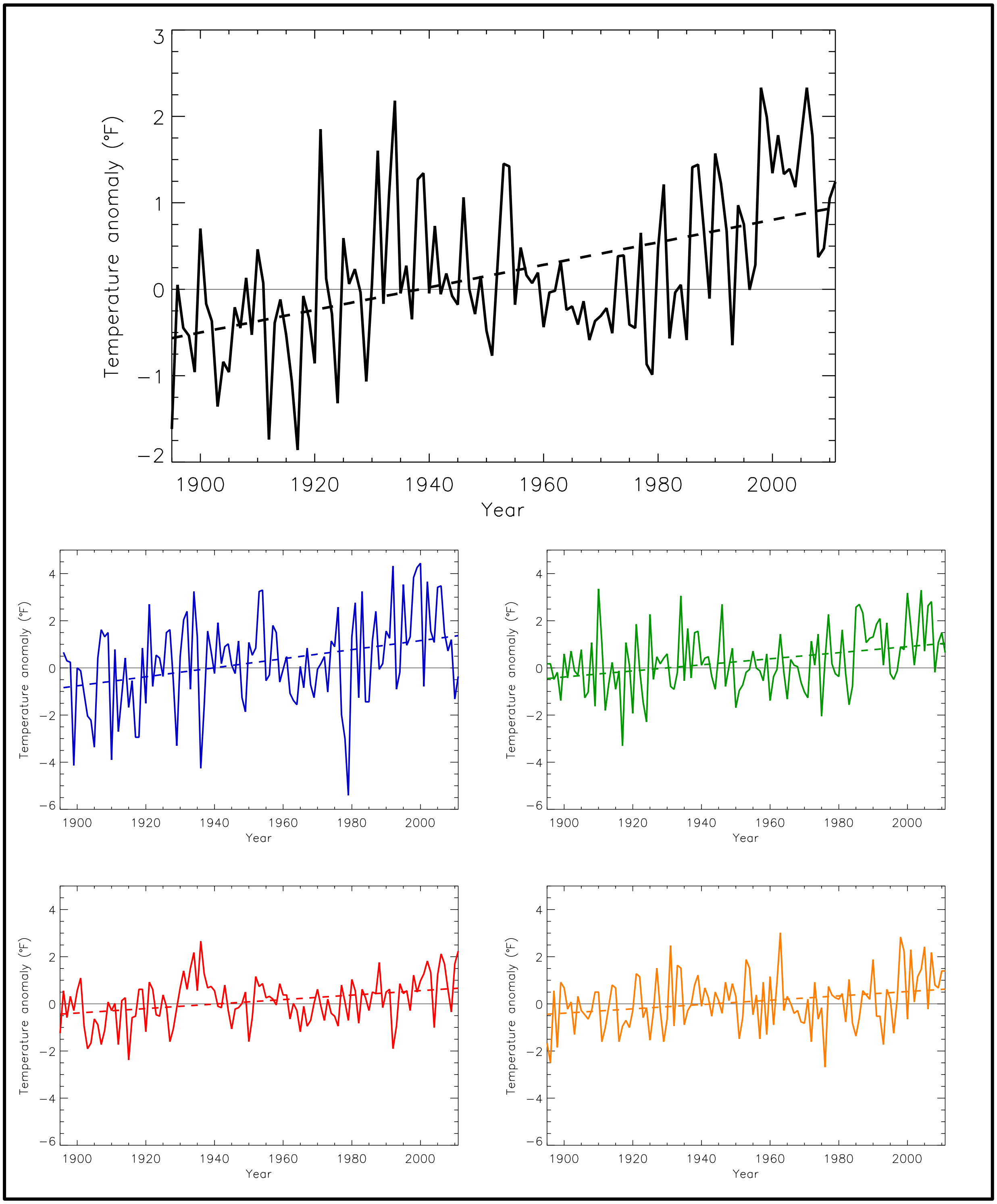

Figure 8. Temperature anomaly (deviations from the 1901-1960 average, °F) for annual (black), winter (blue), spring (green), summer (red), and fall (orange), for the contiguous U.S. Dashed lines indicate the best fit by minimizing the chi-square error statistic. Based on a new gridded version of COOP data from the National Climatic Data Center, the CDDv2 data set (R. Vose, personal communication, July 27, 2012). Note that the annual time series is on a unique scale. Trends are upward and statistically significant annually and for all seasons.

2.4.2. Precipitation

Figure 9 shows annual and seasonal time series of precipitation anomalies for the period of 1895-2011, again calculated using the CDDv2 data set. Annual precipitation (Fig. 9, top) across the contiguous U.S. has exhibited a slight overall upward trend since the early 20th century. It was wetter than normal during the 1990s, drier than normal during the early 2000s, and generally wetter than normal during the last few years. The early 1950s were a very dry multi-year period. The 1930s were nearly as dry. The driest single year on record was 1910. The wettest single year on record was 1973. Seasonal precipitation does not exhibit any sizeable trends (Fig. 9, middle and bottom); overall seasonal variability is least in winter. The trends in Fig. 9 are only statistically significant for the fall season and the year as a whole.

Trends in precipitation for the period of 1895-2011 can be seen in Table 2. Again, only values statistically significant at the 95% confidence level are displayed. Trends are not statistically significant in most regions and seasons. The exceptions are observed upward trends for fall and annual in the Northeast, fall in the Southeast, summer and annual in the Midwest, and annual in the Great Plains. A downward trend is seen for summer in the Southeast.

Table 2. 1895-2011 trends in precipitation anomaly (inches/decade) based on a new gridded version of COOP data from the National Climatic Data Center, the CDDv2 data set (R. Vose, personal communication, July 27, 2012) for the six NCA regions of the continental U.S. (including the northern and southern Great Plains), for each season as well as the year as a whole. Only values statistically significant at the 95% confidence level are displayed. Statistical significance of trends was assessed using Kendall's tau coefficient. The test using tau is a non-parametric hypothesis test.

Region	**Winter**	**Spring**	**Summer**	**Fall**	**Annual**
Contiguous U.S.	—	—	—	+0.10	+0.16
Northeast	—	—	—	+0.24	+0.39
Southeast	—	—	−0.10	+0.27	—
Midwest	—	—	+0.10	—	+0.31
Great Plains	—	—	—	—	+0.14
North	—	—	—	—	—
South	—	—	—	—	—
Northwest	—	—	—	—	—
Southwest	—	—	—	—	—

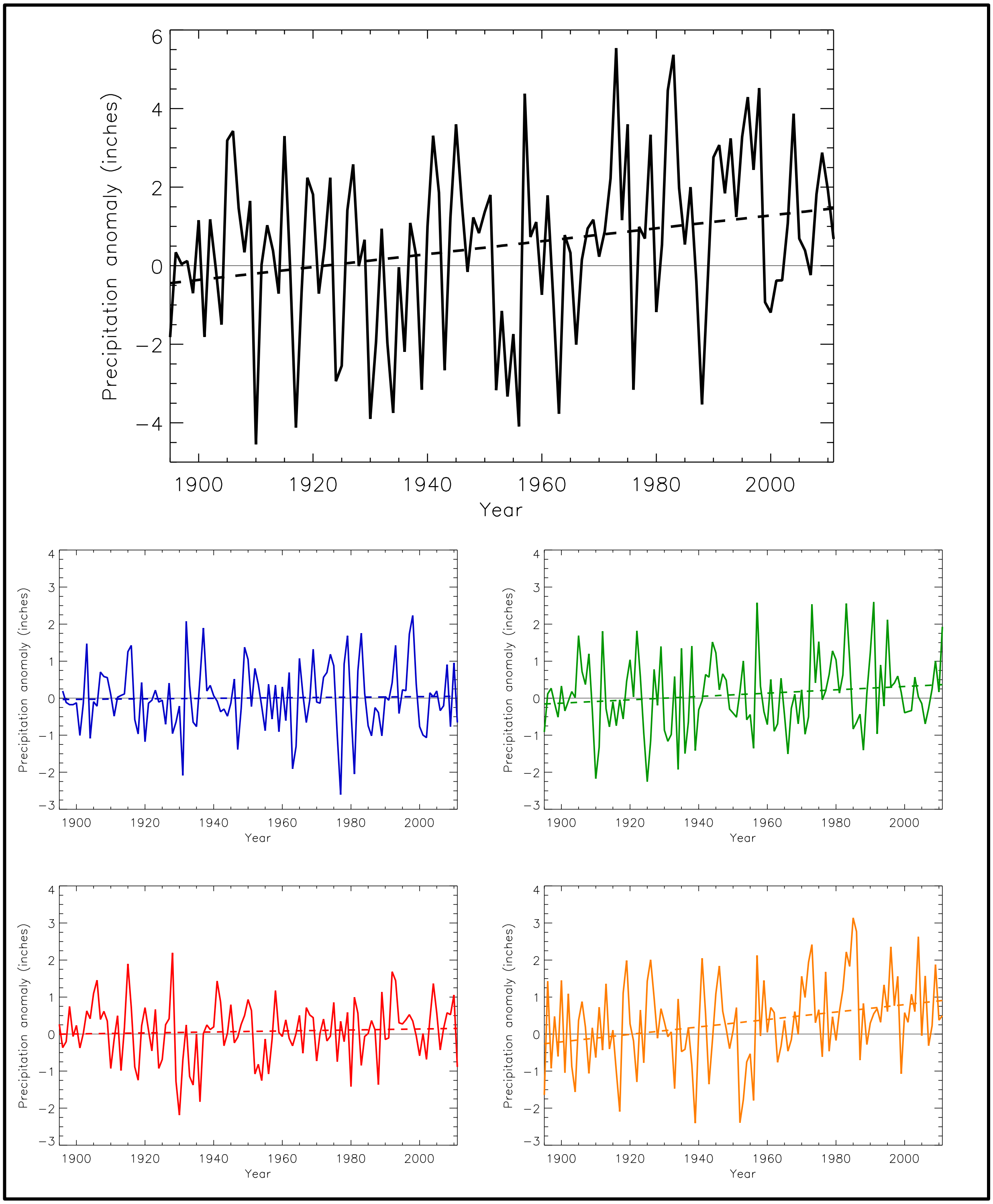

Figure 9. Precipitation anomaly (deviations from the 1901-1960 average, %) for annual (black), winter (blue), spring (green), summer (red), and fall (orange), for the contiguous U.S. Dashed lines indicate the best fit by minimizing the chi-square error statistic. Based on a new gridded version of COOP data from the National Climatic Data Center, the CDDv2 data set (R. Vose, personal communication, July 27, 2012). Note that the annual time series is on a unique scale. Trends are upward and statistically significant annually and for the fall season.

2.4.3. *Extreme Heat and Cold*

Figures 10 and 11 show time series of indices of the number of 4-day long cold wave and heat wave events, exceeding a 1 in 5-year recurrence interval for the period of 1901-2011, for the U.S. as a whole (top right) and for each of the contiguous U.S. NCA regions, calculated using daily COOP data from long-term stations. For the U.S. as a whole (top right), the number of heat wave occurrences was highest in the 1930s and lowest in the 1960s. The 2001-2011 decade was the second highest, but still well below the 1930s. On a regional basis, the western regions had the highest number of occurrences in the 2000s while the 1930s were the highest in the other regions, except for the 1910s in the northeast. There were a moderately high number of heat waves in the 2000s in the Great Plains-North and Northeast. By contrast, the number was quite low in the Midwest and Great Plains-South.

For cold wave occurrences, the national average value was highest in the 1980s and lowest in the 2000s. The lack of cold waves in the 2000s was prevalent throughout the contiguous U.S. with five of the seven regions experiencing their fewest cold waves of the entire period, the only exceptions being the Northeast and Southeast. The 1950s were also a period of few severe cold waves. An analysis of trends over the entire 1895-2011 period, using the Kendall tau non-parametric test, indicates that most trends are not statistically significant. The exception is the Southwest where both cold wave (downward at 8%/decade) and heat wave (upward at 9%/decade) trends are statistically significant.

2.4.4. *Extreme Precipitation*

Figure 12 includes time series of decadal values of an index of the number of 2-day extreme precipitation events exceeding a 1 in 5-year recurrence interval for the period of 1901-2011, for the U.S. as a whole (top right) and for each of the contiguous U.S. NCA regions, again calculated using daily COOP data from long-term stations. For the U.S. as a whole, there is a gradual increase in the index. The highest decadal value is the most recent decade of 2001-2011. For the regions, there is considerable decadal-scale variability whose behavior often varies spatially (e.g., Mass et al. 2011). However, since 1991, all regions have experienced a greater than normal occurrence of extreme events. In the eastern regions, the recent numbers are the largest since reliable records begin (1895). For western regions, the recent decades are comparable to the early part of the historical record. Using the non-parametric Kendall's tau test for trends, the increase is statistically significant for the U.S. as a whole and the individual regions of the Midwest and Southeast.

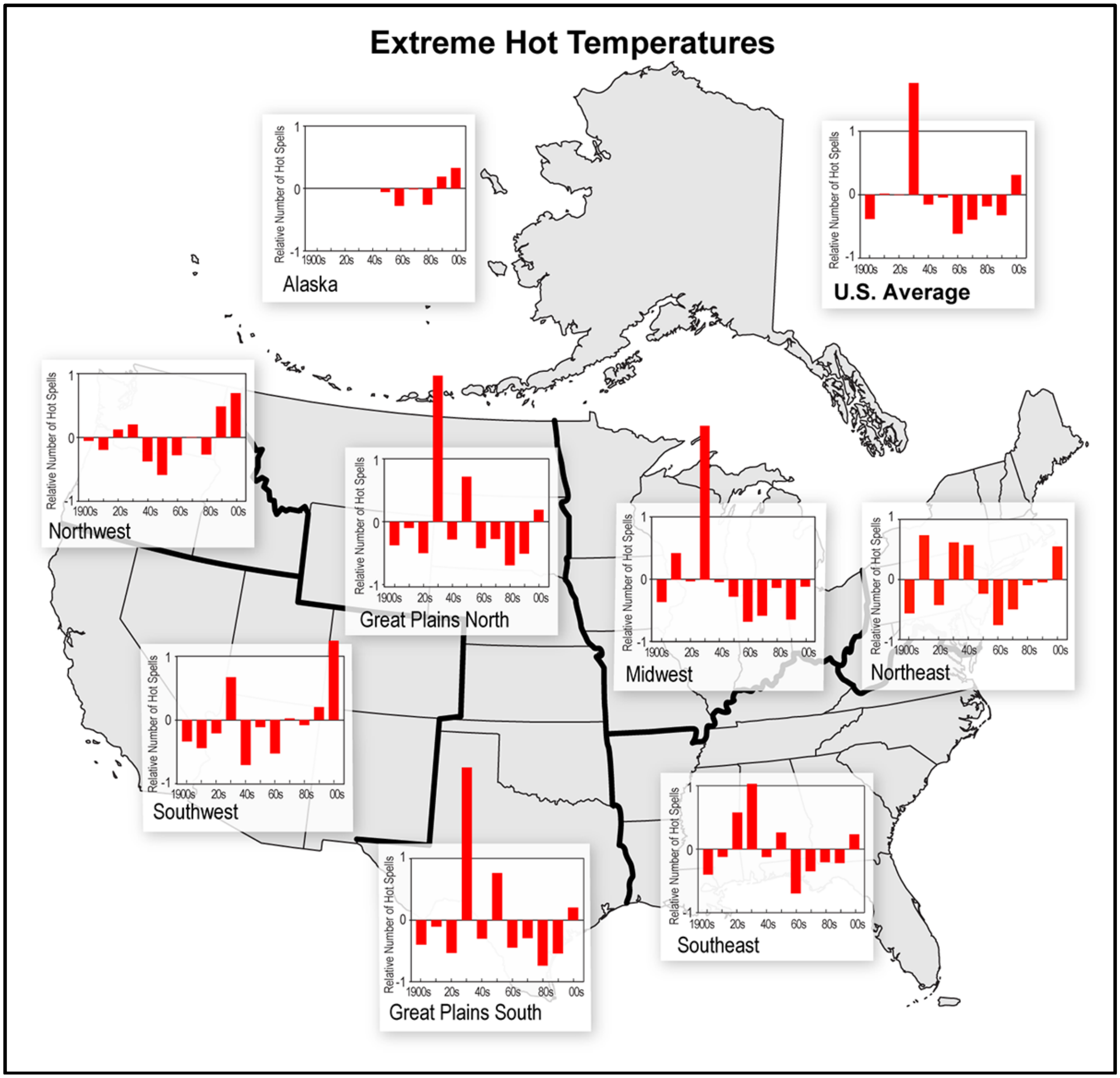

Figure 10. Time series (1901-2011) of decadal average values of heat wave indices for spells of 4-day duration exceeding the threshold for a 1-in-5 year recurrence, based on daily COOP data from long-term stations in the National Climatic Data Center's Global Historical Climate Network data set. Only stations with less than 10% missing daily temperature data are used in this analysis. Individual station events are first identified by sorting 4-day running average mean temperature values and selecting the top Y/R events, where Y is the number of years with data and R is the recurrence interval. Then, annual grid box values are calculated as the #events/#stations with data. Finally, regional values are calculated as the average values of the grid boxes within the region. The index values are normalized to a long-term average value of 1.0. Index values that are above (below) average are upward (downward). The horizontal labels indicate the decade. The far right bar in each graph represents the 11-year period of 2001-2011.

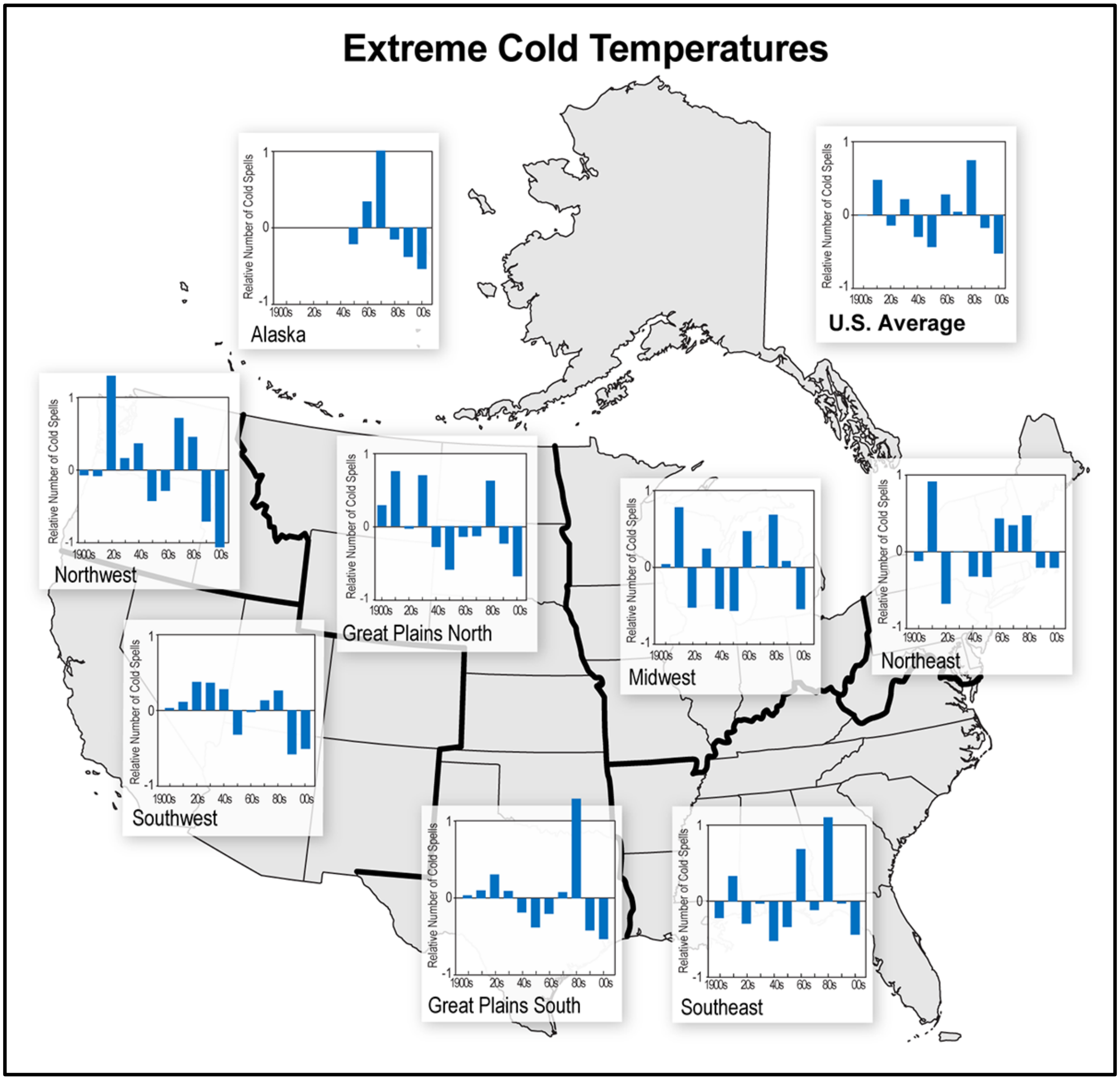

Figure 11. Time series (1901-2011) of decadal average values of cold wave indices for spells of 4-day duration exceeding the threshold for a 1-in-5 year recurrence, based on daily COOP data from long-term stations in the National Climatic Data Center's Global Historical Climate Network data set. Only stations with less than 10% missing daily temperature data are used in this analysis. Individual station events are first identified by sorting 4-day running average mean temperature values and selecting the top Y/R events, where Y is the number of years with data and R is the recurrence interval. Then, annual grid box values are calculated as the #events/#stations with data. Finally, regional values are calculated as the average values of the grid boxes within the region. The index values are normalized to a long-term average value of 1.0. Index values that are above (below) average are upward (downward). The horizontal labels indicate the decade. The far right bar in each graph represents the 11-year period of 2001-2011.

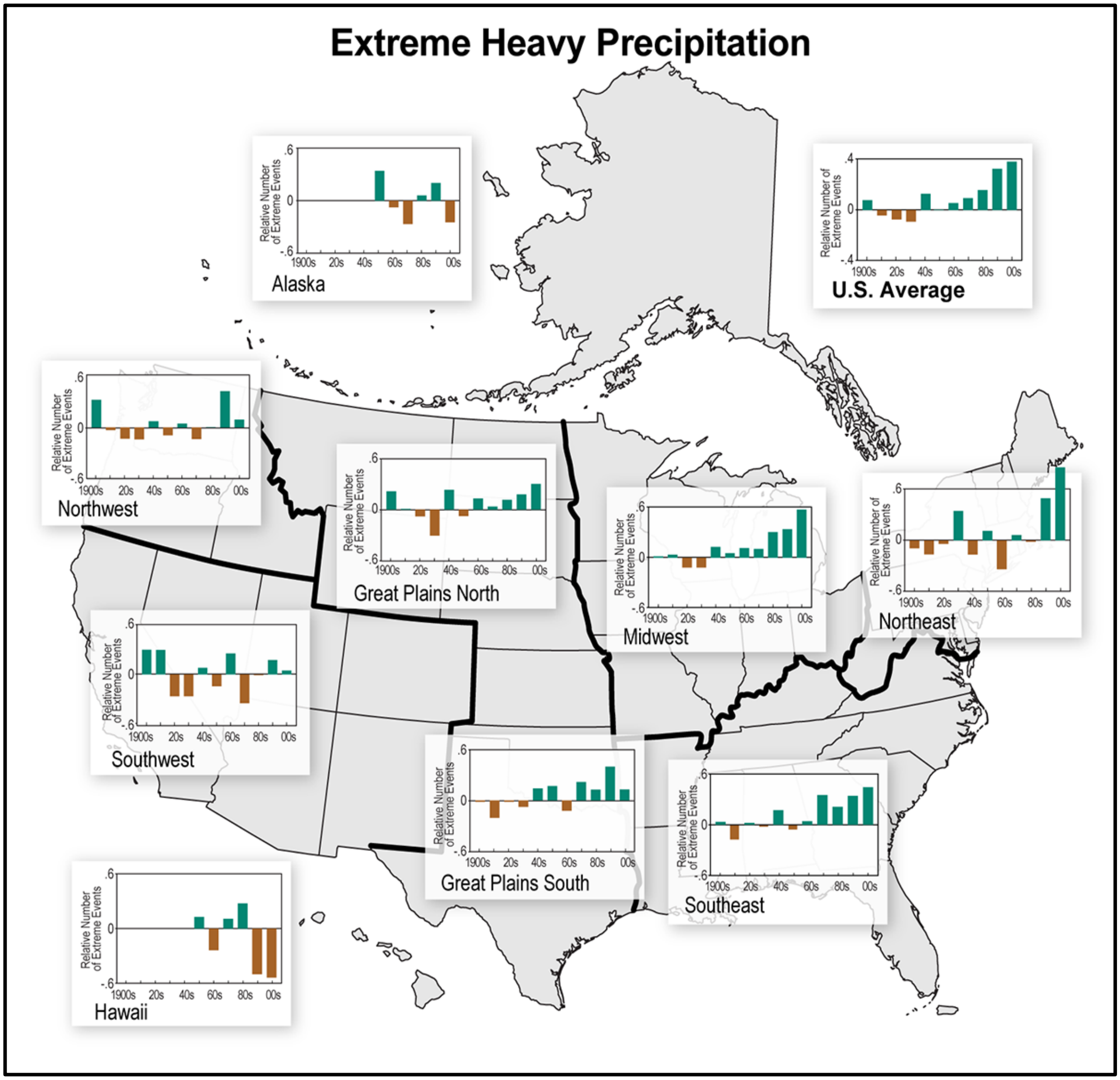

Figure 12. Time series (1901-2011) of decadal values of an index (standardized to 1) of the number of 2-day precipitation totals exceeding a threshold for a 1 in 5-year occurrence for 7 regions and the U.S. as a whole, expressed as the deviation from the long-term average. This was based on daily COOP data from long-term stations in the National Climatic Data Center's Global Historical Climate Network data set. Only stations with less than 10% missing daily temperature data are used in this analysis. Events are first identified for each individual station by ranking all daily precipitation values and choosing the top N/5 events, where N is the number of years of data for that particular station. Then, event numbers for each year are averaged for all stations in each 1x1° grid box. Next, a regional average is determined by averaging the values for the individual grid boxes. Finally, the results were averaged over decadal periods. The far right bar in each graph represents the 11-year period of 2001-2011.

2.4.5. *Freeze-Free Season*

Figure 13 shows time series of freeze-free season length, calculated using the daily COOP data from long-term stations. There has been a general increasing trend since the early 20th century in the length of the freeze-free season (Fig. 13, top). The last occurrence of 32°F in the spring has been occurring earlier, and the first occurrence of 32°F in the fall has been happening later. The average freeze-free season length during 1991-2010 was about 9 days longer than during 1961-1990.

The change in freeze-free season has been somewhat greater in the western U.S. than the eastern U.S., as shown in Fig. 13, bottom. In this figure, separate time series are shown for stations east of 100°W and west of 100°W. In the west, the change in freeze-free season since the beginning of the 20th century has been about 3 weeks, compared to about 10 days for the eastern U.S.

2.4.6. *Water Levels*

Variations in lake levels, if the lakes are carefully chosen, can provide important insights into climate variations. The levels of natural lakes that are not heavily used for irrigation or other consumptive purposes will vary in an integrated response to precipitation, snowfall, temperature, and other variables that affect evaporation.

Levels of the Great Lakes (Fig. 14) have fluctuated over a range of three to six feet since the late 19th century. Lake levels fluctuate due to changes in precipitation and runoff over the basin, evaporation over the lakes, and outflow from the lakes. Higher lake levels were generally noted in the latter part of the 19th century and early 20th century, the 1940s and 1950s, and the 1980s. Lower lake levels were observed in the 1920s and 1930s and again in the 1960s. For the deeper lakes, Superior and Michigan-Huron, the first decade of the 21st century has also seen lower levels. Trends on the lakes have been relatively small with the exception of Lake Michigan-Huron, which has shown a downward trend over the past 150 years.

The Great Salt Lake is a particularly valuable source of information on climate variations because its brackish waters are not suitable for irrigation. Thus, its variations in levels contain a large component of climate variations. Variations in the level of Great Salt Lake have been observed since the earliest settlers (Fig. 15). Note that precipitation is related to the slope of the curve rather than the level itself. Evaporation does not vary as much from year to year as does streamflow input, which is mainly from the Wasatch Mountains and the Uinta Range to the east. The total range of lake levels has been around 20 feet. Highest levels were observed around 1870 and 1986. Levels during the early 21st century have been rather low.

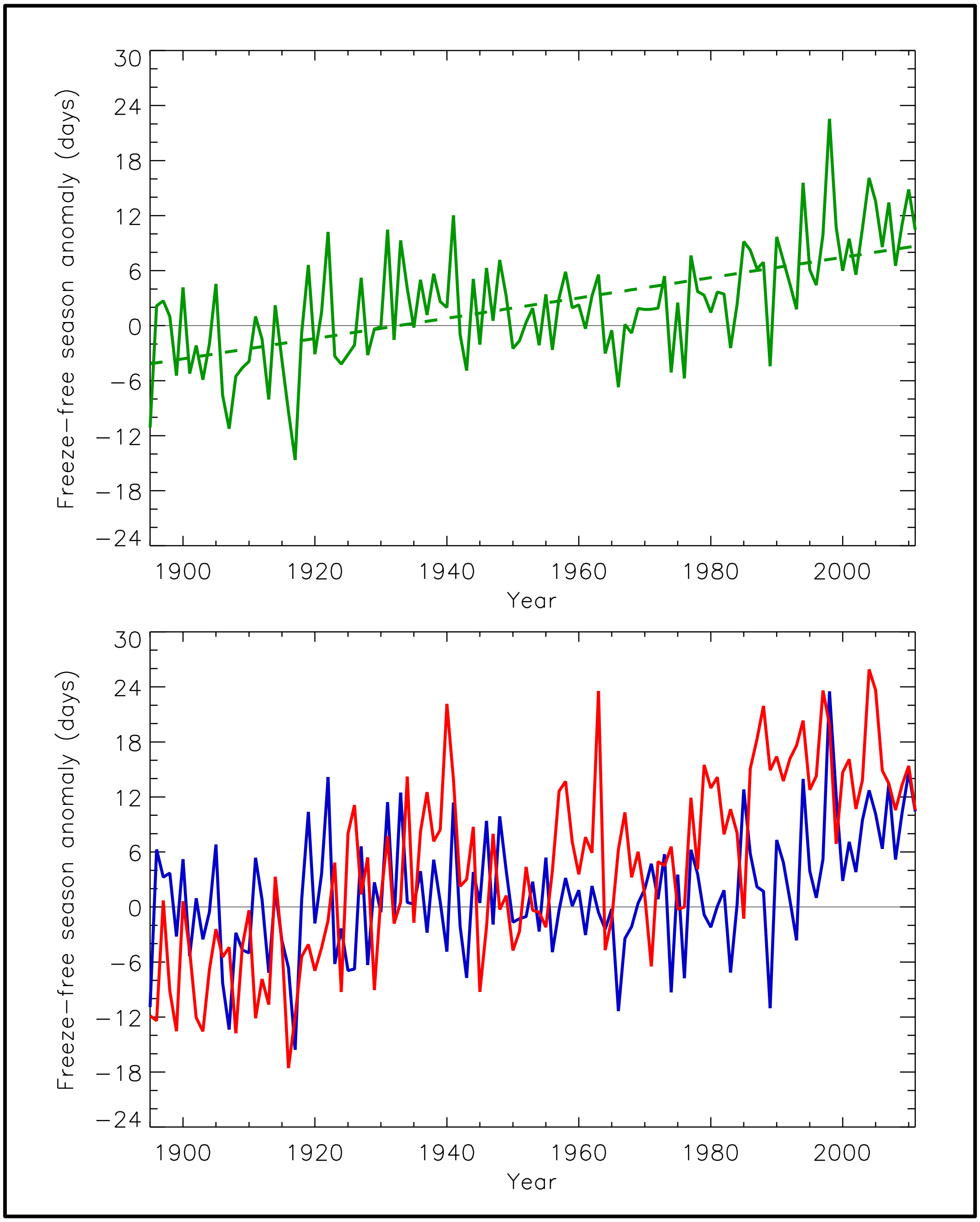

Figure 13. Time series of freeze-free season anomalies shown as the number of days per year, for the contiguous U.S. (top, green), eastern U.S. (bottom, blue) and western U.S. (bottom, red). Length of the freeze-free season is defined as the period between the last occurrence of 32°F in the spring and first occurrence of 32°F in the fall. The dashed line is a linear fit. Based on daily COOP data from long-term stations in the National Climatic Data Center's Global Historical Climate Network data set. Only stations with less than 10% missing daily temperature data for the period 1895-2011 are used in this analysis. Freeze events are first identified for each individual station. Then, event dates for each year are averaged for 1x1° grid boxes. Finally, a regional average is determined by averaging the values for the individual grid boxes. There is an overall statistically significant upward trend for the contiguous U.S., as well as for both the eastern and western U.S.

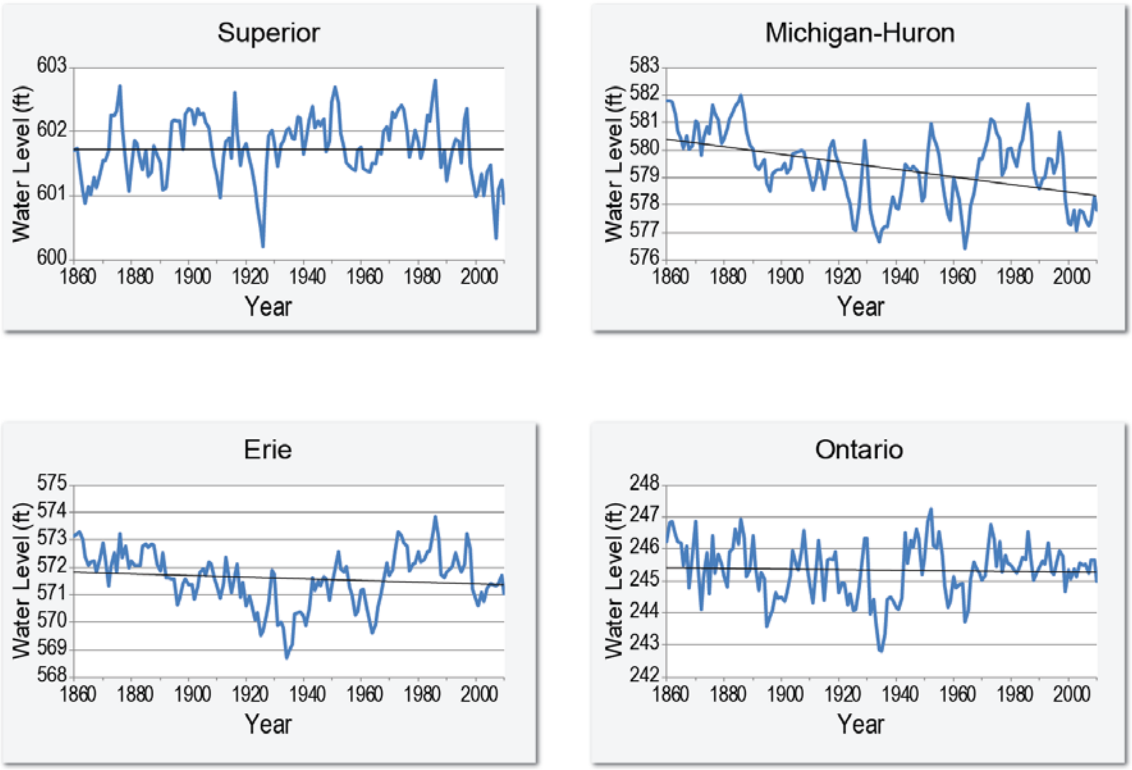

Figure 14. Hydrographs of lake levels for each of the Great Lakes from 1860 to 2010. The linear trend of the lake level time series are shown by the straight black lines. Some fluctuations are noted across the lakes while other variability is specific to a particular lake. Data from the NOAA Great Lakes Environmental Research Laboratory (NOAA GLERL 2012). The trend for Michigan-Huron is downward and statistically significant.

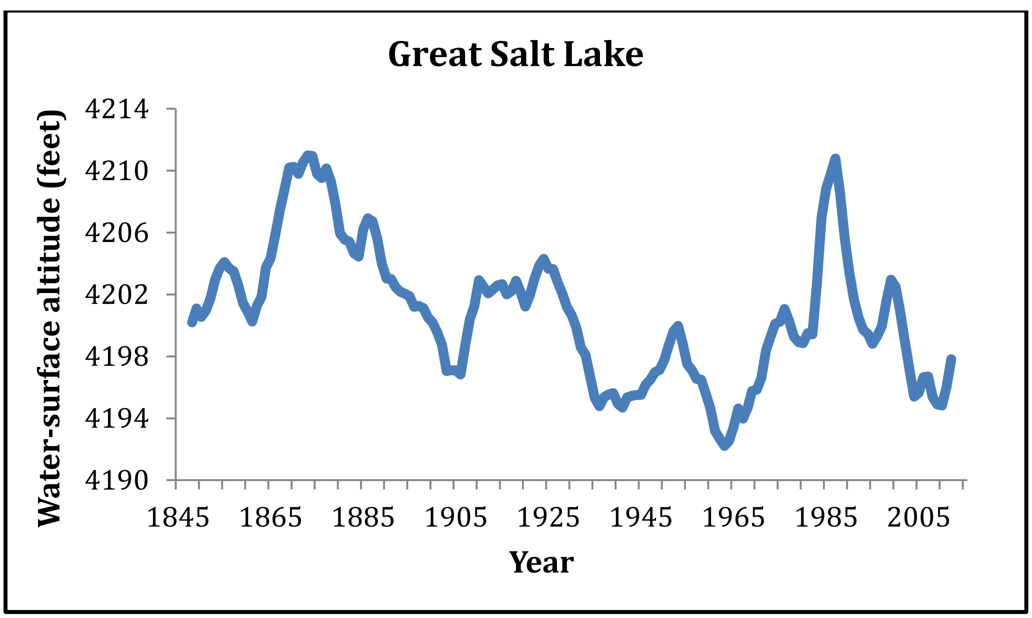

Figure 15. Great Salt Lake elevation, estimated and observed, from USGS (2012).

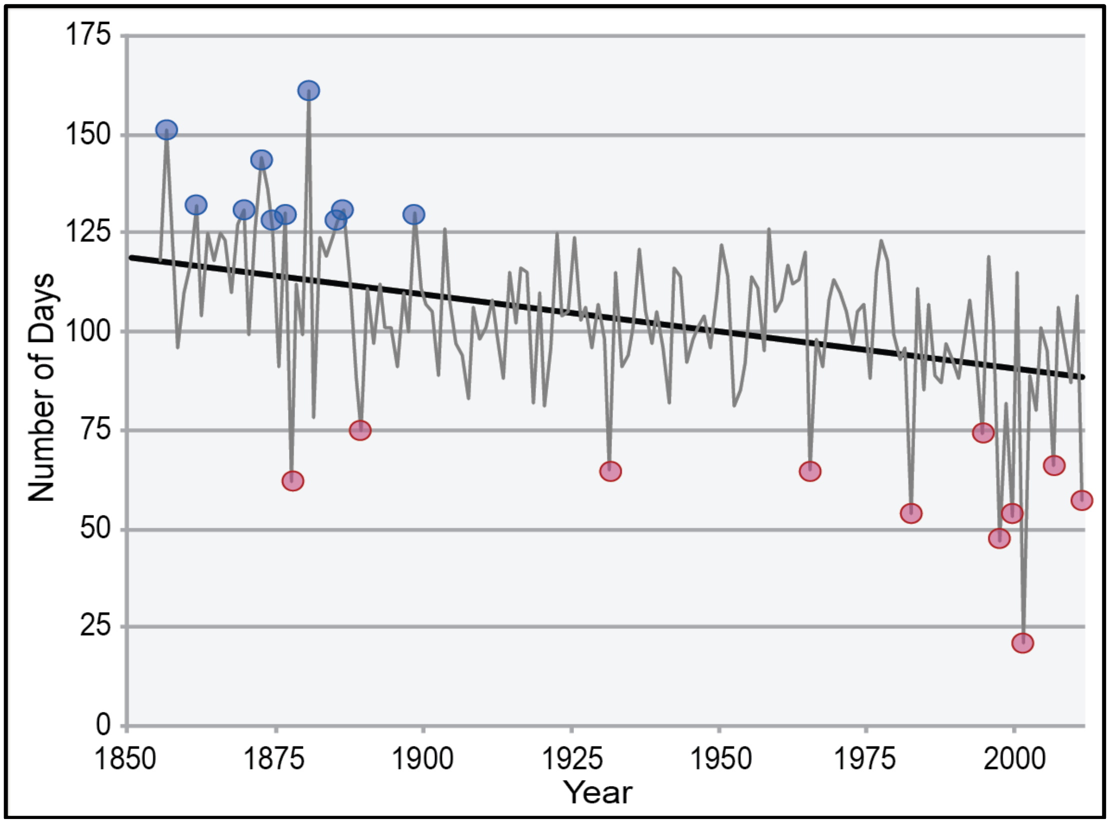

Figure 16. Long-term change in ice-cover duration for Lake Mendota, WI. The 10 longest and 11 shortest ice seasons are marked by blue and red circles, respectively. There has been a consistent downward trend and 7 of the 10 shortest ice cover seasons have occurred since 1980 (Wisconsin State Climatology Office 2012).

2.4.7. Ice Cover

Measurements of ice cover on lakes in the northern U.S. generally indicate a negative trend in length of the period with ice cover or percentage of total ice cover. The total duration of ice cover on Lake Mendota in Madison, WI (Fig. 16), exhibits a consistent downward trend, decreasing from about 120 days in the late 19th century to less than 100 days in most years since 1990. The average ice cover on the Great Lakes (Fig. 17) has gradually declined since the 1970s.

A long-term record of the date of ice-in on Lake Champlain in Vermont shows that the lake now freezes approximately two weeks later than it did in the early 1800s and over a week later than it did 100 years ago (Fig. 18). Later ice-in dates are an indication of warmer lake temperatures, as it takes longer for the warmer water to freeze in winter. Prior to 1950, the absence of winter ice cover on Lake Champlain was rare, occurring three times in the 1800s and another three times between 1900 and 1940. Since 1970 Lake Champlain has remained ice-free during 18 winters.

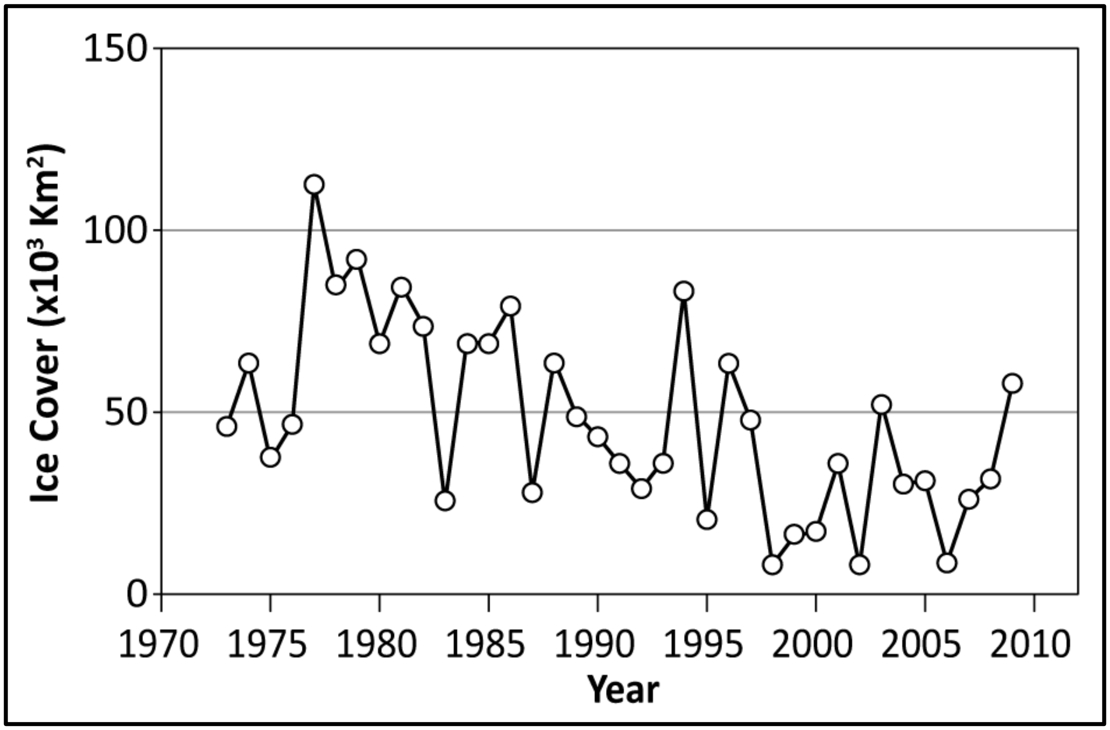

Figure 17. Time series of annual-averaged ice area for the Great Lakes. There has been a general downward trend over the last 30 years. Republished with permission of the American Geophysical Union, adapted from Wang et al. (2010); permission conveyed through Copyright Clearance Center, Inc.

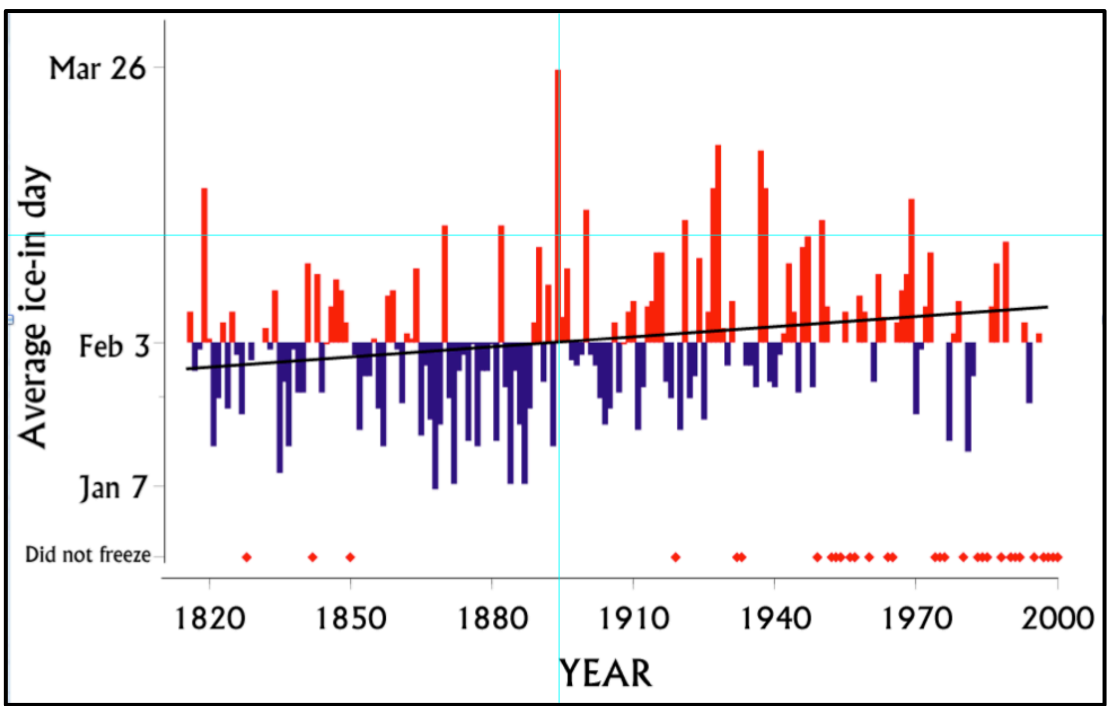

Figure 18. Time series of date of ice-in on the main portion of Lake Champlain. Asterisks denote years in which the lake remained ice-fee. Data from NOAA (2012b).

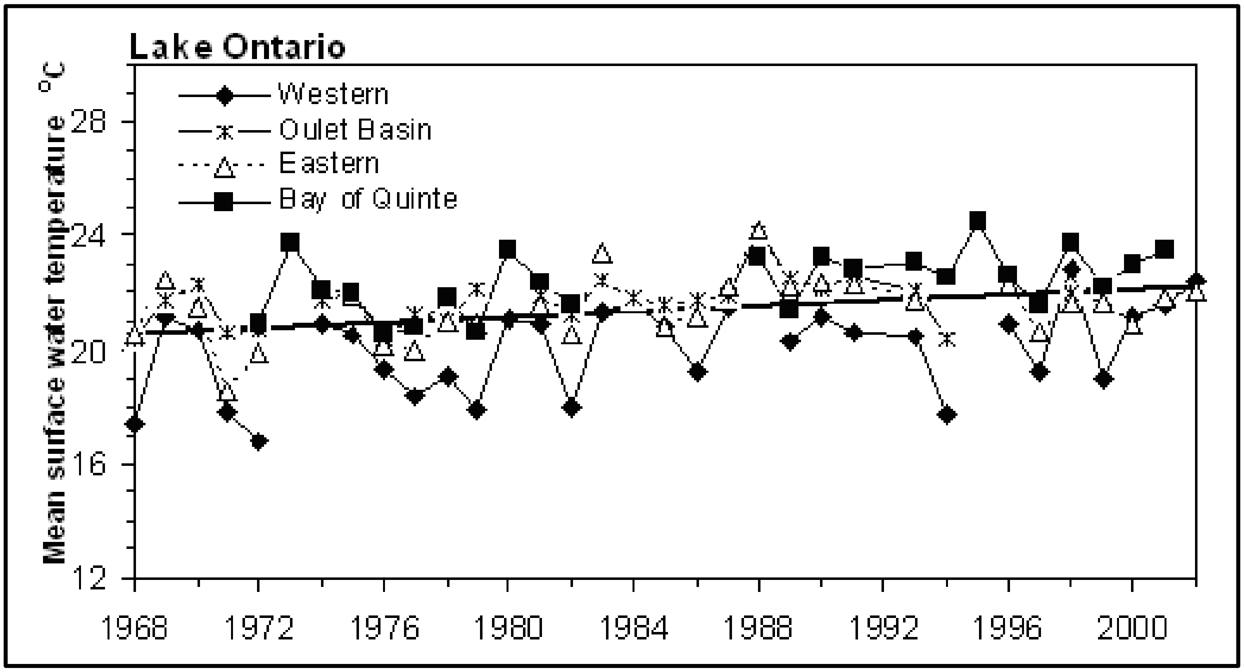

Figure 19. Surface water temperatures in four sub-basins of Lake Ontario in August. Republished with permission of Elsevier, from Dobiesz and Lester (2009); permission conveyed through Copyright Clearance Center, Inc.

2.4.8. Great Lakes Water Temperature

In addition to levels, lake water temperatures are also an important climate indicator for the Lakes. They affect the health of the Lake's ecosystems, the cooling capacity of lakeshore power generation plants and influence the potential for winter lake-effect snow. Figure 19 shows a time series (1968-2002) of surface water temperature from different sections of Lake Ontario (Dobiesz and Lester 2009). Significant trends toward warmer lake temperatures are apparent in three of the four sub basins. Across the four basins, temperatures have increased by more than 5°F. Surface water temperatures in Lake Erie have also increased, but at a much lower rate.

3. FUTURE NATIONAL CLIMATE SCENARIOS

As noted above, the physical climate framework for the 2013 NCA report is based on climate model simulations of the future using the high (A2) and low (B1) SRES emissions scenarios. The resulting climate conditions are to be viewed as scenarios, not forecasts, and there are no explicit or implicit assumptions about the probability of occurrence of either scenario.

3.1. Description of Data Sources

This summary of future regional climate scenarios is based on the following model data sets:

- **Coupled Model Intercomparison Project phase 3 (CMIP3) –** Fifteen coupled Atmosphere-Ocean General Circulation Models (AOGCMs) from the World Climate Research Programme (WCRP) CMIP3 multi-model dataset (PCMDI 2012), as identified in the 2009 NCA report (Karl et al. 2009), were used: CCSM3, CGCM3.1 (T47), CNRM-CM3, CSIRO-Mk3.0, ECHAM5/MPI-OM, ECHO-G, GFDL-CM2.0, GFDL-CM2.1, INM-CM3.0, IPSL-CM4, MIROC3.2 (medres), MRI-CGCM2.3.2, PCM; UKMO-HadCM3, and UKMO-HadGEM1. The spatial resolution of the great majority of these model simulations was 2-3° (a grid point spacing of approximately 100-200 miles), with a few slightly greater or smaller. All model data were re-gridded to a common resolution before processing (see below). The simulations from all of these models include:

  a) Simulations of the 20th century using best estimates of the temporal variations in external forcing factors (such as greenhouse gas concentrations, solar output, volcanic aerosol concentrations); and

  b) Simulations of the 21st century assuming changing greenhouse gas concentrations following both the A2 and B1 emissions scenarios. One of the fifteen models did not have a B1 simulation.

- **North American Regional Climate Change Assessment Program (NARCCAP) –** This multi-institutional program is producing regional climate model (RCM) simulations in a coordinated experimental approach (NARCCAP 2012). At the time that this data analysis was initiated, simulations were available for 9 different combinations of an RCM driven by a general circulation model (GCM); during the development of these documents, two additional simulations became available and were incorporated into selected products. These 11 combinations involved four different GCMs and six different RCMs (see Table 3). The mean temperature and precipitation maps include all 11 combinations. For calculations and graphics involving the distribution of NARCCAP models, analyses of only the original 9 model combinations were used. For graphics of the number of days exceeding thresholds and the number of degree days, the values were obtained from the Northeast Regional Climate Center, where only 8 of the model combinations were analyzed.

  Each GCM-RCM combination performed simulations for the periods of 1971-2000, 1979-2004 and 2041-2070 for the high (A2) emissions scenario only. These simulations are at a resolution of approximately 50 km (~30 miles), covering much of North America and adjacent ocean areas. The simulations for 1971-2000 and 2041-2070 are "driven" (time-dependent conditions on the lateral boundaries of the domain of the RCM are provided) by global climate model simulations. The 1979-2004 simulations are driven by the NCEP/DOE Reanalysis II data set, which is an estimate of the actual time-dependent state of the atmosphere using a model that incorporates observations; thus the resulting simulations are the RCM's representation of historical observations. From this 1979-2004 simulation, the interval of 1980-2000 was selected for analysis.

Table 3. Combinations of the 4 GCMs and 6 RCMs that make up the 11 NARCCAP dynamically-downscaled model simulations.

		GCMs			
		CCSM3	CGCM3.1	GFDL-CM2.1	UKMO-HadCM3
RCMs	CRCM	X	X		
	ECPC			X[2]	
	HRM3			X[3]	X
	MM5I	X			X[3]
	RCM3		X	X	
	WRFG	X	X		

3.2. Analyses

Analyses are provided for the periods of 2021-2050, 2041-2070, and 2070-2099, with changes calculated with respect to an historical climate reference period (either 1971-1999, 1971-2000, or 1980-2000). These future periods will sometimes be denoted in the text by their midpoints of 2035, 2055, and 2085, respectively.

As noted above, three different intervals are used as the reference period for the historical climatology. Although a uniform reference period would be ideal, there were variations in data availability and in the needs of the author teams. For the NARCCAP maps of mean temperature and precipitation, the 1971-2000 period was used as the reference because that represents the full historical simulation period. The 1971-1999 period (rather than 1971-2000) was used as the reference for CMIP3 maps because some of the CMIP3 models' 20th century simulations ended in 1999, but we wanted to keep the same starting date of 1971 for both CMIP3 and NARCCAP mean temperature and precipitation maps. The 1980-2000 period was used as the historical reference for some of the NARCCAP maps (days over thresholds and degree days) because this is the analyzed period of the reanalysis-driven simulation, and we were requested to provide maps of the actual values of these variables for both the historical period and the future period, and not just a difference map. A U.S.-wide climatology based on actual observations was not readily available for all of these variables, and we chose to use the reanalysis-driven model simulation as an alternative. Since the reanalysis data set approximates observations, the reanalysis-driven RCM simulation will be free from biases arising from a driving GCM. To produce the future climatology map of actual values, we added the (future minus historical) differences to the 1980-2000 map values. For

[3] Data from these model combinations were not used for simulations of the number of days exceeding thresholds or degree days, or calculations and graphics involving the distribution of NARCCAP models.

consistency then, the differences between future and present were calculated using the 1980-2000 subset of the 1971-2000 GCM-driven simulation.

Three different types of analyses are represented, described as follows:

- **Multi-model mean maps –** Model simulations of future climate conditions typically exhibit considerable model-to-model variability. In most cases, the future climate scenario information is presented as multi-model mean maps. To produce these, each model's data is first re-gridded to a common grid of approximately 2.8° latitude (~190 miles) by 2.8° longitude (~130-170 miles). Then, each grid point value is calculated as the mean of all available model values at that grid point. Finally, the mean grid point values are mapped. This type of analysis weights all models equally. Although an equal weighting does not incorporate known differences among models in their fidelity in reproducing various climatic conditions, a number of research studies have found that the multi-model mean with equal weighting is superior to any single model in reproducing the present-day climate (Overland et al. 2011). In most cases, the multi-model mean maps include information about the variability of the model simulations. In addition, there are several graphs that show the variability of individual model results. These should be examined to gain an awareness of the magnitude of the uncertainties in each scenario's future values.
- **Spatially-averaged products –** To produce these, all the grid point values within the Southeast region boundaries are averaged and represented as a single value. This is useful for general comparisons of different models, periods, and data sources. Because of the spatial aggregation, this product may not be suitable for many types of impacts analyses.
- **Probability density functions (pdfs) –** These are used here to illustrate the differences among models. To produce these, spatially-averaged values are calculated for each model simulation. Then, the distribution of these spatially-averaged values is displayed. This product provides an estimate of the uncertainty of future changes in a tabular form. As noted above, this information should be used as a complement to the multi-model mean maps.

3.3. Mean Temperature

Figure 20 shows the spatial distribution of multi-model mean simulated differences in average annual temperature for the three future time periods (2035, 2055, 2085) relative to the model reference period of 1971-1999, for both emissions scenarios, for the 14 (B1) or 15 (A2) CMIP3 models. The statistical significance regarding the change in temperature between each future time period and the model reference period was determined using a 2-sample t-test assuming unequal variances for those two samples. For each period (present and future climate), the mean and standard deviation were calculated using the 29 or 30 annual values. These were then used to calculate t. In order to assess the agreement between models, the following three categories were determined for each grid point, similar to that described in Tebaldi et al. (2011):

- *Category 1*: If less than 50% of the models indicate a statistically significant change then the multi-model mean is shown in color. Model results are in general agreement that simulated changes are within historical variations;
- *Category 2*: If more than 50% of the models indicate a statistically significant change, and less than 67% of the significant models agree on the sign of the change, then the grid points are masked out, indicating that the models are in disagreement about the direction of change;

- *Category 3*: If more than 50% of the models indicate a statistically significant change, and more than 67% of the significant models agree on the sign of the change, then the multi-model mean is shown in color with hatching. Model results are in agreement that simulated changes are statistically significant and in a particular direction.

It can be seen from Fig. 20 that all three future time periods indicate an increase in temperature throughout the U.S., compared to the reference period of 1971-1999, which is a continuation of the climatological upward trend of the last 30 years. Spatial variations are generally small, with the exception of the high (A2) emissions scenario for 2085, which shows more pronounced warming toward the northern parts of the country. This is consistent with global analyses that show relatively gradual spatial changes on a global scale (Meehl et al. 2007), a probable consequence of the generally high instantaneous spatial coherence of temperature and the smoothing effect of multi-model averaging. Coastal areas exhibit less warming than areas inland, and this pattern becomes more defined with time. Both scenarios and all areas show increased temperature change as time progresses, and the differences between the two scenarios also increase with time, with A2 being warmer.

Values are similar for the two scenarios in 2035, ranging from 1.5 to 3.5°F. By 2055, the A2 scenario is roughly 1°F warmer than the B1 in all areas, with warming ranging from 2.5 to 5.5°F. In the 2085 simulation, the low (B1) emissions scenario shows a warming that closely resembles the A2 scenario from 30 years prior, while the A2 scenario shows large warming in all areas, with temperature increases ranging from 4.5°F in Florida to 9.5°F in the upper Midwest. The CMIP3 models indicate that temperature changes across the United States, for all three future time periods and both emissions scenarios, are statistically significant. The models also agree on the sign of change, with all grid points satisfying category 3 above, i.e. the models are in agreement on temperature increases throughout the region for each future time period and scenario.

Figure 21 shows the multi-model mean simulated annual and seasonal 30-year average temperature changes between 2041-2070 and 1971-2000 for the high (A2) emissions scenario, for 11 NARCCAP regional climate model simulations. The simulated annual changes are generally uniform, with most areas experiencing warming between 3.5 and 5.0°F. However, some seasons show more spatial variability. Spring shows the least warming in most areas, ranging from 2.5-3.5°F over most of the country to 3.5-4.5°F in the southwestern and northeastern parts of the country. Fall shows the same level of spatial uniformity, with values ranging from 2.5°F in the Pacific Northwest to 5.5°F over the center of the country. The winter season shows a general south to north gradient in simulated temperature changes, with the greatest warming (up to 6.5°F) occurring in the northern reaches of the country, and the least (2.5-3.0°F) occurring along the Gulf and Pacific coasts. Finally, summer is characterized by a swath of enhanced warming across the central Rockies and Great Plains, up to 6.5°F, from Nevada to western Kentucky. The magnitude of simulated temperature changes decreases outward from this region, but all areas are simulated to experience warming of at least 3.5°F. The agreement between models was again assessed using the three categories described in Fig. 20. The models agree on the sign of change, with all grid points satisfying category 3, annually, and for all seasons.

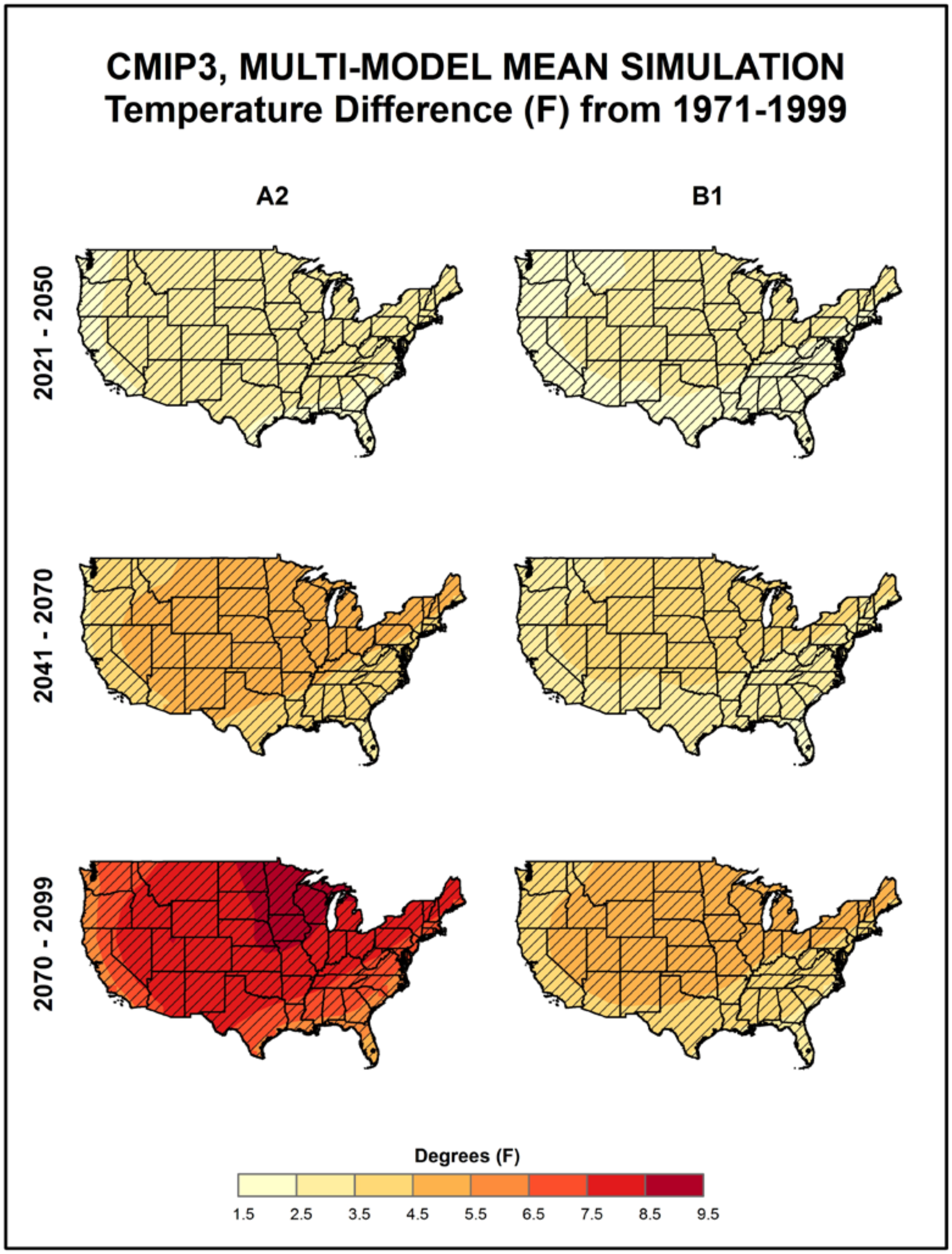

Figure 20. Simulated difference in annual mean temperature (°F) for the contiguous United States, for each future time period (2021-2050, 2041-2070, and 2070-2099) with respect to the reference period of 1971-1999. These are multi-model means for the high (A2) and low (B1) emissions scenarios from the 14 (B1) or 15 (A2) CMIP3 global climate simulations. Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in temperature, and more than 67% agree on the sign of the change (see text). Temperature changes increase throughout the 21st century, more rapidly for the high emissions scenario.

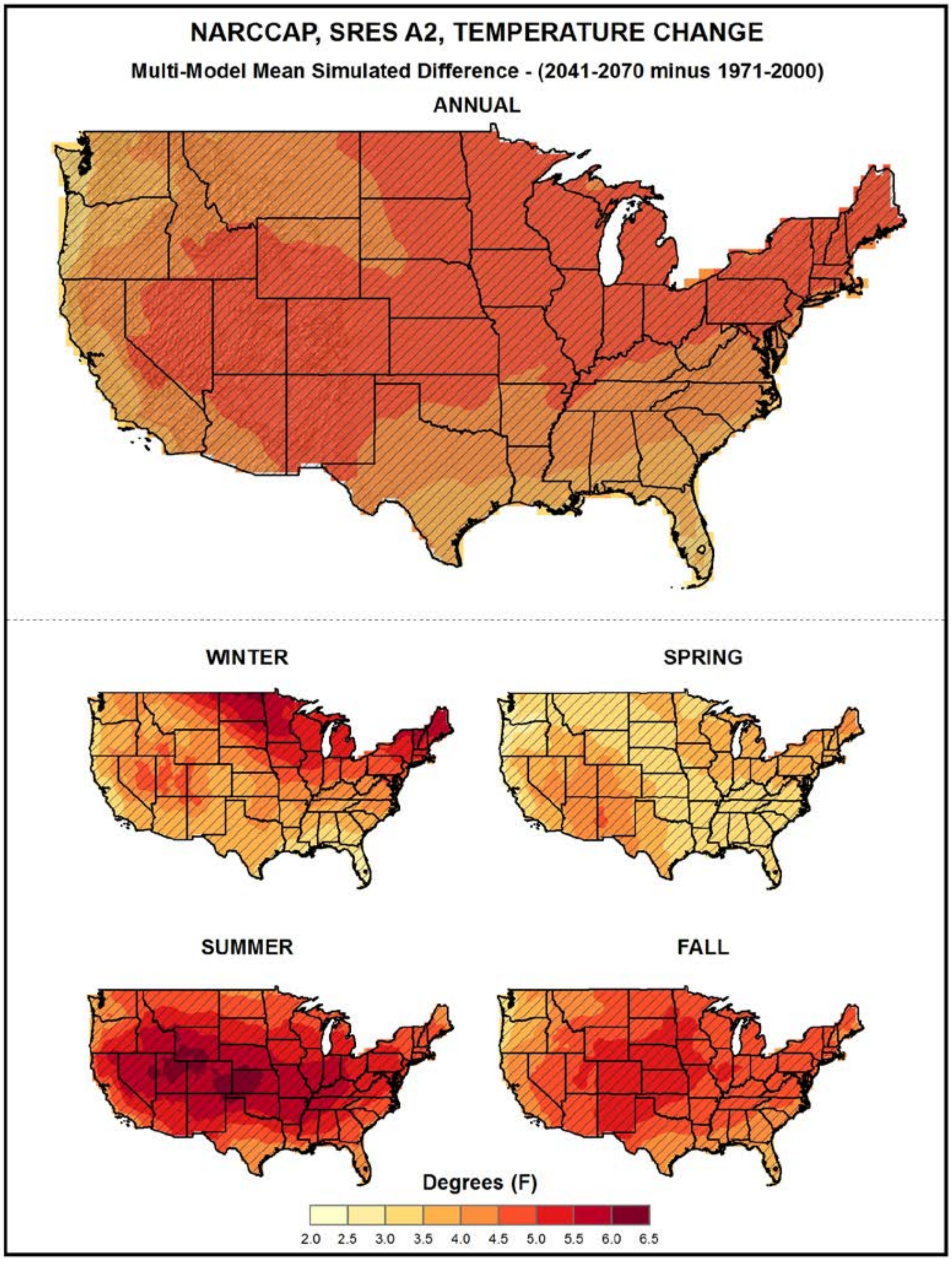

Figure 21. Simulated difference in annual and seasonal mean temperature (°F) for the contiguous United States, for 2041-2070 with respect to the reference period of 1971-2000. These are multi-model means from 11 NARCCAP regional climate simulations for the high (A2) emissions scenario. Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in temperature, and more than 67% agree on the sign of the change (see text). Note that the color scale is different from that of Fig. 20. Annual temperature changes for the NARCCAP simulations are similar to those for the CMIP3 global models (Fig. 20, middle left panel). Seasonal changes are greatest for summer and smallest for spring.

Figure 22 shows the simulated change in annual mean temperature for each future time period with respect to 1971-1999, for both emissions scenarios, averaged over the entire continental U.S. for the 14 (B1) or 15 (A2) CMIP3 models. In addition, values for 9 of the NARCCAP simulations and the 4 GCMs used in the NARCCAP experiment are shown for 2055 (A2 scenario only) with respect to 1971-2000. Both the multi-model mean and individual model values are shown. For the high (A2) emissions scenario, the CMIP3 models simulate average increases of 2.9°F by 2035, 4.6°F by 2055, and nearly 8°F by 2085. The increases for the low (B1) emissions scenario are nearly as large in 2035 at around 2.5°F, but by 2085 the increase of 4.8°F is just over half of the increase seen in the A2 scenario. For 2055, the average temperature change simulated by the NARCCAP models (4.3°F) is close to the mean of the CMIP3 GCMs for the A2 scenario. Note that the rate of observed warming was about 1.3°F since 1900 (see Table 1); thus the simulated rates of warming for the 21st century are much larger than the 20th century observed rates, even for the low emissions scenario.

A key overall feature is that the simulated temperature changes are similar in value for the high and low emissions scenarios for 2035, but largely different for 2085. This indicates that early in the 21st century, the multi-model mean temperature changes are relatively insensitive to the emissions pathway, whereas late 21st century changes are quite sensitive to the emissions pathway. This arises because atmospheric CO_2 concentrations resulting from the two different emissions scenarios do not considerably diverge from one another until around 2050 (see Fig. 1). It can also be seen from Fig. 22 that the range of individual model changes is quite large, with considerable overlap between the A2 and B1 results, even for 2085. The range of temperature changes for the GCMs used to drive the NARCCAP simulations is small relative to the range for all CMIP3 models. This may be largely responsible for the relatively small range of the NARCCAP models.

Figure 23 shows the simulated change in seasonal mean temperature for each future time period with respect to 1971-1999 for the high (A2) emissions scenario, averaged over the entire continental U.S. for the 15 CMIP3 models. Again, both the multi-model mean and individual model values are shown. The largest average warming is consistently simulated for the summer season, while winter and spring indicate the least amount of warming. For all seasons, this warming is simulated to increase with time. The spread of individual model values is large in all cases, and also increases with time. The models have a range of approximately 2.5°F in 2035, increasing to 6.5°F by 2085.

The distribution of simulated changes in annual mean temperature for each future time period with respect to 1971-1999 for both emissions scenarios among the 14 (B1) or 15 (A2) CMIP3 models is shown in Table 4. These simulated changes range from 1.5°F in 2035 for the low (B1) emissions scenario to 10.7°F in 2085 for the high (A2) emissions scenario. Although the inter-model range of temperature changes (i.e. the difference between the highest and lowest model values) is seen to increase for each future time period, the interquartile range (the difference between the 75th and 25th percentiles) varies less, with values of between 0.7 and 1.6°F across the three time periods. The NARCCAP simulated temperature changes have a smaller range than the comparable CMIP3 simulations, varying from 3.4°F to 5.0°F.

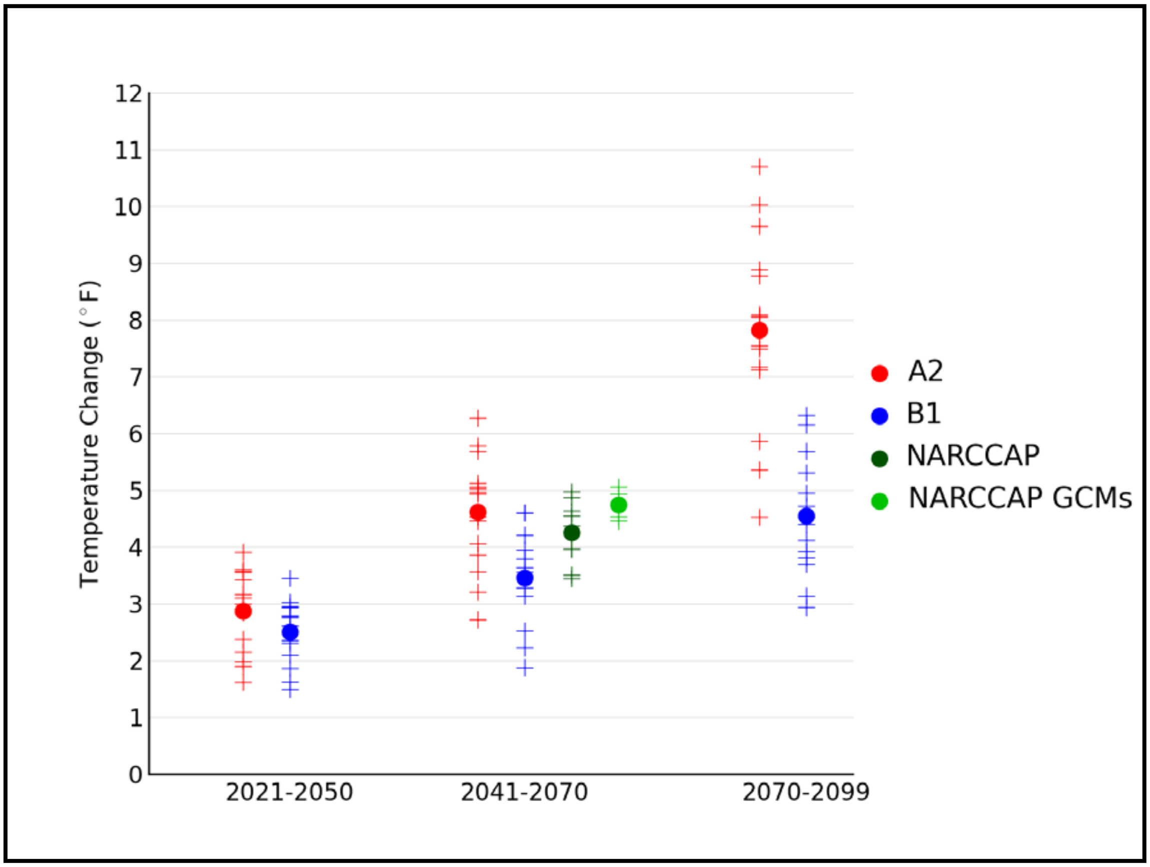

Figure 22. Simulated annual mean temperature change (°F) for the contiguous United States, for each future time period (2021-2050, 2041-2070, and 2070-2099) with respect to the reference period of 1971-1999 for the CMIP3 models and 1971-2000 for the NARCCAP models. Values are given for the high (A2) and low (B1) emissions scenarios for the 14 (B1) or 15 (A2) CMIP3 models. Also shown for 2041-2070 (high emissions scenario only) are values for 9 NARCCAP models, as well as for the 4 GCMs used to drive the NARCCAP simulations. The small plus signs (+) indicate each individual model and the circles depict the multi-model means. The range of model-simulated changes is large compared to the mean differences between A2 and B1 in the early and middle 21st century. By the end of the 21st century, the difference between A2 and B1 is comparable to the range of B1 simulations.

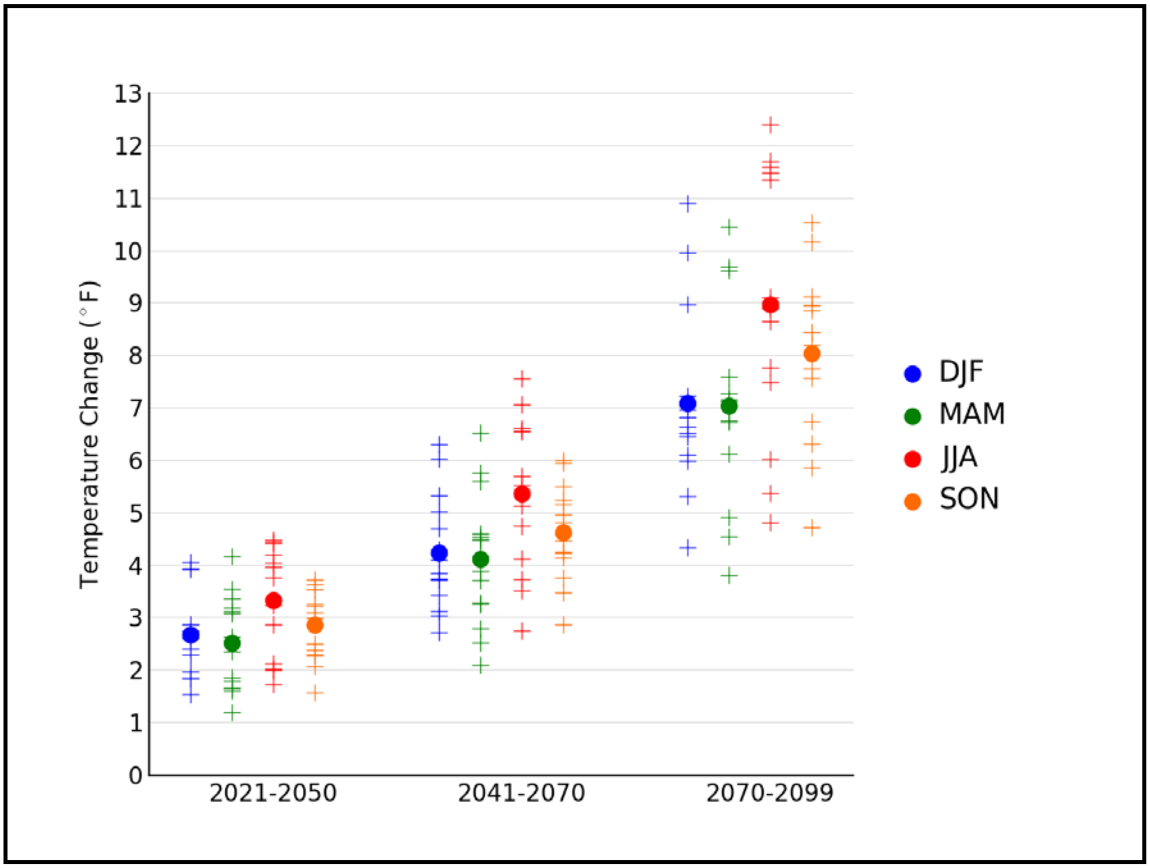

Figure 23. Simulated seasonal mean temperature change (°F) for the contiguous United States, for each future time period (2021-2050, 2041-2070, and 2070-2099) with respect to the reference period of 1971-1999. Values are given for all 15 CMIP3 models for the high (A2) emissions scenario. The small plus signs (+) indicate each individual model and the circles depict the multi-model means. Seasons are indicated as follows: winter (DJF, December-January-February), spring (MAM, March-April-May), summer (JJA, June-July-August), and fall (SON, September-October-November). The range of individual model-simulated changes is large compared to the differences among seasons and comparable to the differences between periods.

Table 4. Distribution of the simulated change in annual mean temperature (°F) from the 14 (B1) or 15 (A2) CMIP3 models for the contiguous United States. The lowest, 25th percentile, median, 75th percentile and highest values are given for the high (A2) and low (B1) emissions scenarios, and for each future time period (2021-2050, 2041-2070, and 2070-2099) with respect to the reference period of 1971-1999. . Also shown are values from the distribution of 9 NARCCAP models for 2041-2070, A2 only, with respect to 1971-2000.

Scenario	Period	Lowest	25th Percentile	Median	75th Percentile	Highest
A2	2021-2050	1.6	2.3	3.0	3.5	3.9
	2041-2070	2.7	4.0	4.9	5.1	6.3
	2070-2099	4.5	7.2	8.0	8.8	10.7
	NARCCAP (2041-2070)	3.4	4.0	4.4	4.6	5.0
B1	2021-2050	1.5	2.2	2.7	2.9	3.5
	2041-2070	1.9	3.2	3.5	3.9	4.6
	2070-2099	2.9	3.8	4.5	5.2	6.3

This table also illustrates the overall uncertainty arising from the combination of model differences and emission pathway. For 2035, the simulated changes range from 1.5°F to 3.9°F and are almost entirely due to differences in the individual models. By 2085, the range of simulated changes has increased to 2.9°F to 10.7°F, with roughly equal contributions to the range from model differences and emission pathway uncertainties.

3.4. Extreme Temperature

A number of metrics of extreme temperatures were calculated from the NARCCAP dynamically-downscaled data set. Maps of a few select variables follow. Each figure of NARCCAP data includes three map panels and the calculations used in each panel require some explanation. One panel (top) shows the difference between the 2055 period (2041-2070) simulation for the high (A2) emissions scenario and the 1980-2000 subset of the 1971-2000 simulation driven by the GCM. Since biases in the RCM simulations can arise from biases either in the driving global climate model or in the RCM, these two simulations include both sources of biases. It is usually assumed that such biases will be similar for historical and future periods. When taking the difference of these, the biases should at least partially cancel. As noted above, we were requested to include actual values of the variables, not just the future minus historical differences. We decided that the best model representation of the present-day values is the 1980-2000 simulation because it is driven by reanalysis data (NOAA 2012c) and thus will not include biases from a driving global climate model (although the reanalysis data used to drive the RCM is not a perfect representation of the actual state of the atmosphere). Any biases should be largely from the RCM. Thus, the lower left panel in the following figures shows the actual values from the 1980-2000 simulation. The lower right panel shows the actual values for the future period, calculated by adding the differences (the 2041-2070 simulation minus the 1980-2000 subset of the 1971-2000 simulation) to the 1980-2000 simulation. If our assumption that the differencing of present and future at least partially cancels out model biases is true, then the predominant source of biases in the future values in the lower right hand panel is from the RCM simulation of the present-day, 1980-2000, simulation. The agreement among models was assessed using the three categories described in Fig. 20.

The selection of threshold temperatures to calculate extremes metrics is somewhat arbitrary because impacts-relevant thresholds are highly variable due to the very diverse climate of the U.S., with the exception of the freezing temperature, which is a universal physical threshold. In terms of high temperature thresholds, the values of 90°F, 95°F, and 100°F have been utilized in various studies of heat stress, although it is obvious that these thresholds have very different implications for the impacts on northern, cooler regions compared to southern, warmer regions. The threshold of 95°F has physiological relevance for maize production because the efficiency of pollination drops above that threshold. The low temperature thresholds of 10°F and 0°F also have varying relevance on impacts related to the background climate of a region. Fortunately, our analysis is not qualitatively sensitive to the chosen thresholds. Thus, the results for these somewhat arbitrary choices nevertheless provide general guidance into scenarios of future changes.

Figure 24 shows the spatial distribution of the multi-model mean change in the average annual number of days with a maximum temperature exceeding 95°F between 2055 and the model reference period, for the high (A2) emissions scenario, for 8 NARCCAP regional climate model simulations. The largest simulated increases of more than 25 days occur in the Southeast and Southwest regions, as well as the southern portion of the southern Great Plains. These are also the areas with the greatest number of days exceeding 95°F in the historical period. The NARCCAP models indicate that the changes in the number of 95°F days across the majority of the U.S. are statistically significant. The models also agree on the sign of change, with these grid points satisfying category 3, i.e. the models are in agreement that the number of days above 95°F will increase. However, for some portions of the country (the far northwest U.S., northern Minnesota, northern Maine, and the Rocky Mountains) the changes are not statistically significant for most models (category 1). In these areas where the historical number of days is very small, the models are in agreement that the increases in temperature are not sufficiently large to substantially increase the number of such days under this scenario.

Figure 25 shows the NARCCAP multi-model mean change in the average annual number of days with a minimum temperature of less than 10°F between 2055 and the model reference period, for the high (A2) emissions scenario. A large decrease in the number of days is simulated along the Rocky Mountains and in the northernmost states, compared to little or no change in southern regions. The largest absolute decreases are simulated to occur in higher elevation areas with changes of up to 30 days. The smallest decreases occur in southern areas and along the Pacific coast, where the number of occurrences of days below 10°F in both the present-day climate and future periods is zero or near zero, the reason that changes in these areas are not statistically significant (category 1). All other grid points satisfy category 3, however, with the models indicating that the changes in the number days below 10°F are statistically significant. The models also agree on the sign of change, i.e. they are in agreement that the number of days with a minimum temperature of less than 10°F will decrease under this scenario.

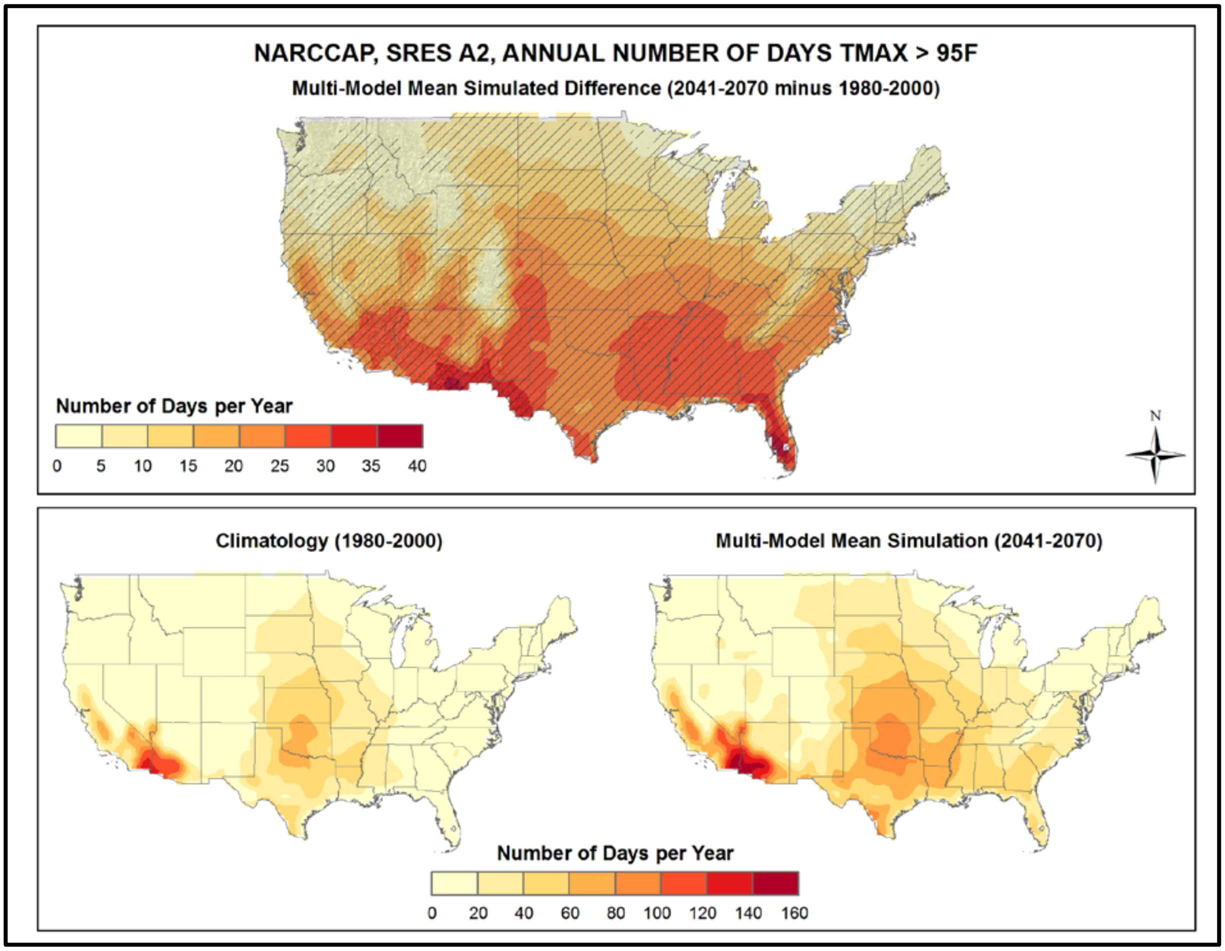

Figure 24. Simulated difference in the mean annual number of days with a maximum temperature greater than 95°F (T_{max} > 95°F) for the contiguous United States, for the 2041-2070 time period with respect to the reference period of 1980-2000 (top). Color only (category 1) indicates that less than 50% of the models show a statistically significant change in the number of days. Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in the number of days, and more than 67% agree on the sign of the change (see text). Mean annual number of days with T_{max} > 95°F for the 1980-2000 reference period (bottom left). Simulated mean annual number of days with T_{max} > 95°F for the 2041-2070 future time period (bottom right). These are multi-model means from 8 NARCCAP regional climate simulations for the high (A2) emissions scenario. Note that top and bottom color scales are different. The changes are upward everywhere. Increases are smallest in the northern U.S. and at high elevations and largest in the far southwest.

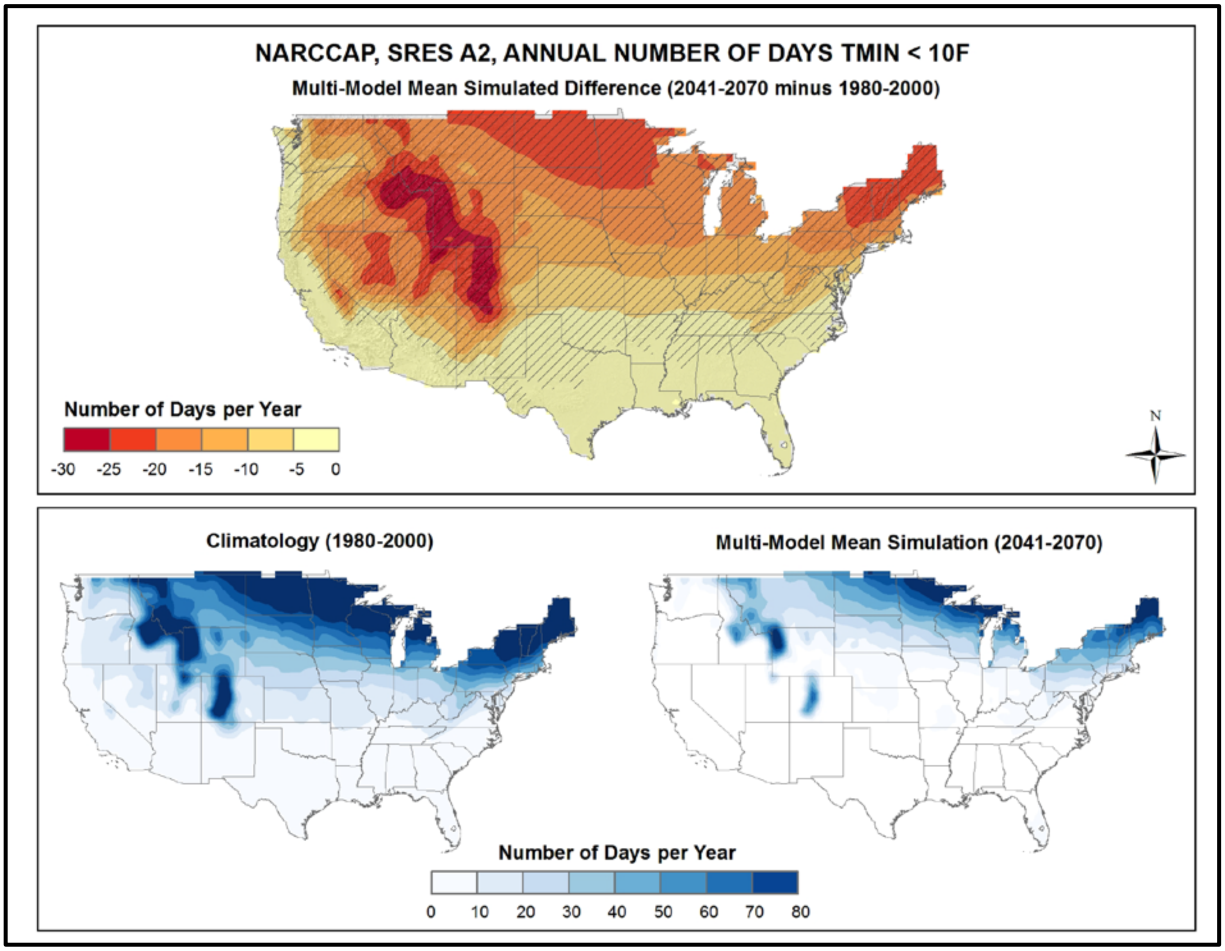

Figure 25. Simulated difference in the mean annual number of days with a minimum temperature less than 10°F (T_{min} < 10°F) for the contiguous United States, for the 2041-2070 time period with respect to the reference period of 1980-2000 (top). Color only (category 1) indicates that less than 50% of the models show a statistically significant change in the number of days. Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in the number of days, and more than 67% agree on the sign of the change (see text). Mean annual number of days with T_{min} < 10°F for the 1980-2000 reference period (bottom left). Simulated mean annual number of days with T_{min} < 10°F for the 2041-2070 future time period (bottom right). These are multi-model means from 8 NARCCAP regional climate simulations for the high (A2) emissions scenario. Decreases are largest at high elevations and are smallest in the south and west, in a pattern similar to the present-day climatology.

Figure 26 shows the NARCCAP multi-model mean change in the average annual number of days with a minimum temperature of less than 32°F between 2055 and the model reference period, for the high (A2) emissions scenario. Model simulated decreases are largest (more than 25 days) in much of the western third of the U.S. Decreases of more than 40 days are simulated for the Sierra Nevada and Cascade mountain ranges. The NARCCAP models indicate that the changes in the number of days below freezing across the U.S. are statistically significant. The models also agree on the sign of change, with all grid points satisfying category 3, i.e. the models are in agreement that the number of days below 32°F will decrease throughout the country under this scenario.

Consecutive warm days can have large impacts on a geographic area and its population and are analyzed here as one metric of heat waves. Figure 27 shows the NARCCAP multi-model mean change in the average annual maximum number of consecutive days with maximum temperatures exceeding 95°F between 2055 and the model reference period, for the high (A2) emissions scenario. The pattern is similar to that of the change in the total number of days exceeding 95°F. In parts of the Southwest region, the average annual longest string of days with such high temperatures is simulated to increase by 20 days or more. Little or no change is seen in the Northwest, Northeast and northern parts of the Midwest. Between 4 and 20 more consecutive 95°F days are simulated for most other areas. For the far northwest U.S. and the Rocky Mountains the changes in the number of consecutive 95°F days are not statistically significant for most models (category 1) because the number of consecutive days is zero or near zero in both the historical and future simulations. For the majority of the U.S., however, changes are statistically significant. The models also agree on the sign of change, with these grid points satisfying category 3, i.e. the models are in agreement that the number of consecutive days above 95°F will increase under this scenario.

3.5. Other Temperature Variables

The spatial distribution of the NARCCAP multi-model mean change in the average length of the freeze-free season between 2055 and the model reference period of 1980-2000, for the high (A2) emissions scenario, is shown in Fig. 28. The freeze-free season is defined as the period of time between the last spring freeze (a daily minimum temperature of less than 32°F) and the first fall freeze. Increases are simulated throughout the Southeast region. Climatologically there has been an upward trend since the early 20th century. Increases of at least 20 more days in the annual freeze-free season are simulated across the majority of U.S. by 2055. The only exceptions are some parts of the northern Great Plains and southern Florida, which show increases of 8-20 days. The largest increases are in the far west with increases of up to 46 days along the Pacific coast. All grid points satisfy category 3, with the models indicating that the changes in the length of the freeze-free season across the U.S. are statistically significant. The models also agree on the sign of change, i.e. the models are in agreement that the freeze-free season length will increase throughout the country under this scenario.

Cooling and heating degree days are accumulative metrics related to energy use, more specifically regarding the cooling and heating of buildings, with a base temperature of 65°F, assumed to be the threshold below which heating is required and above which cooling is required. Heating degree days provide a measure of the extent (in degrees), and duration (in days), that the daily mean temperature is below the base temperature. Cooling degree days measure the extent and duration that the daily mean temperature is above the base temperature.

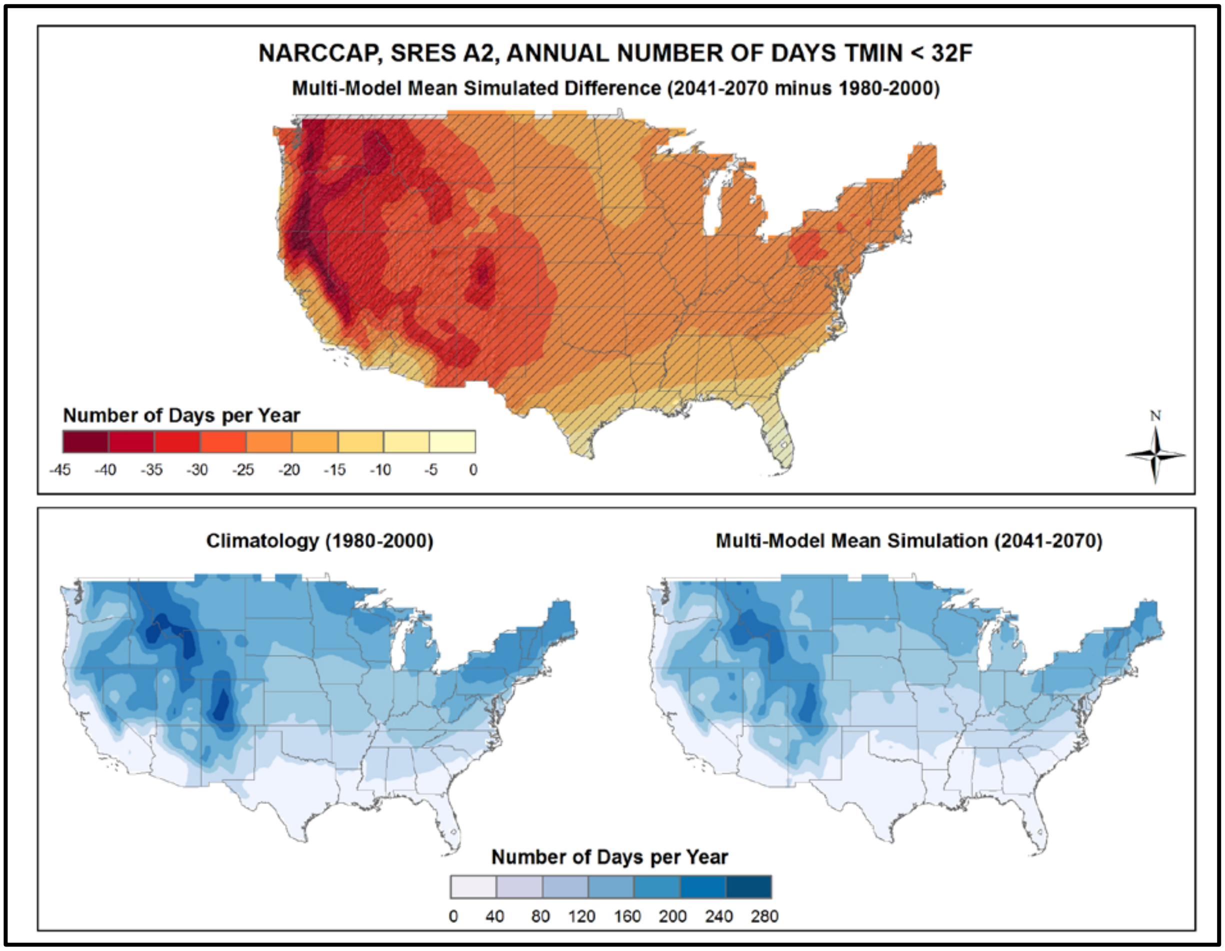

Figure 26. Simulated difference in the mean annual number of days with a minimum temperature less than 32°F (T_{min} < 32°F) for the contiguous United States, for the 2041-2070 time period with respect to the reference period of 1980-2000 (top). Color only (category 1) indicates that less than 50% of the models show a statistically significant change in the number of days. Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in the number of days, and more than 67% agree on the sign of the change (see text) (see text). Mean annual number of days with T_{min} < 32°F for the 1980-2000 reference period (bottom left). Simulated mean annual number of days with T_{min} < 32°F for the 2041-2070 future time period (bottom right). These are multi-model means from 8 NARCCAP regional climate simulations for the high (A2) emissions scenario. Changes are downward everywhere. Decreases are largest in the western U.S. and are smallest in the far southeast.

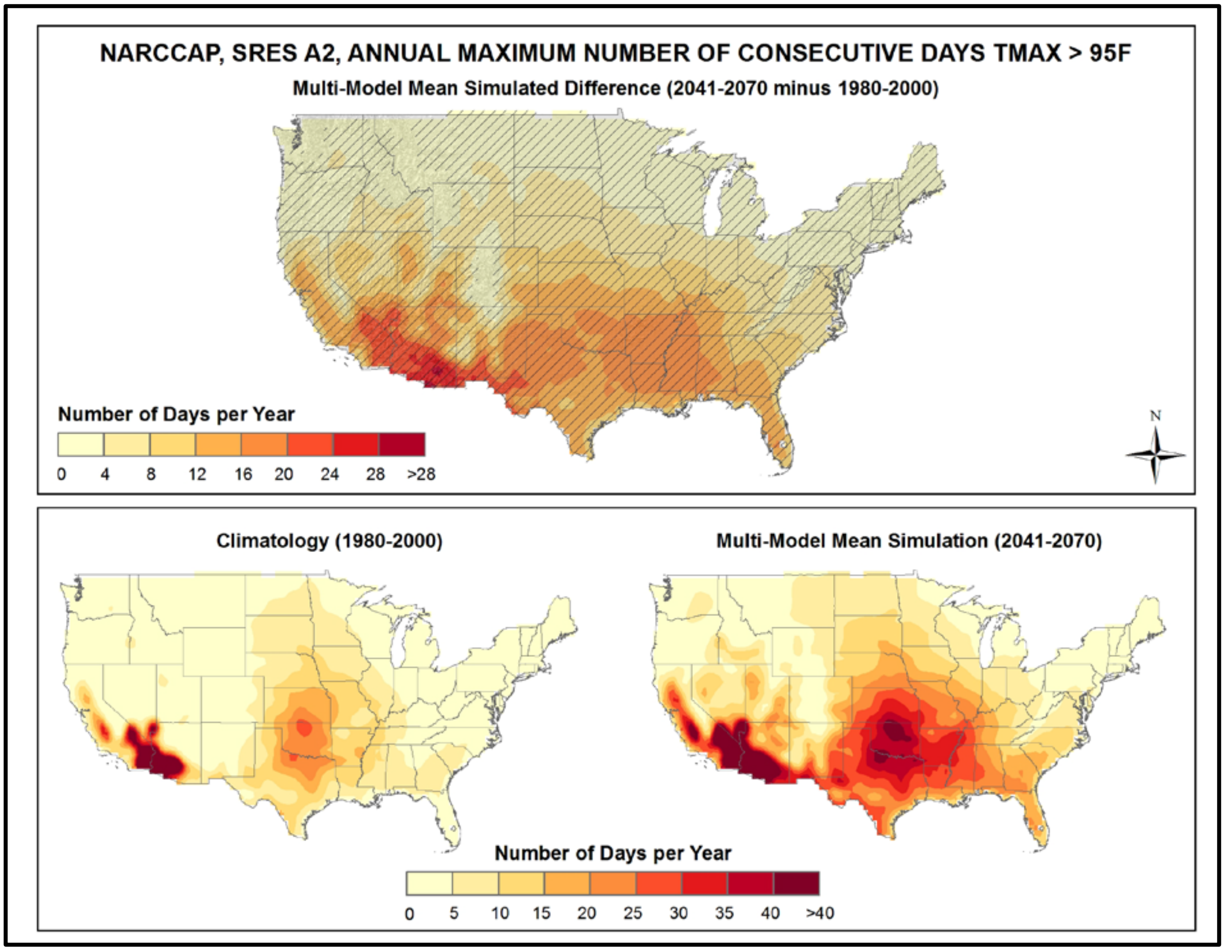

Figure 27. Simulated difference in the mean annual maximum number of consecutive days with a maximum temperature greater than 95°F (T_{max} > 95°F) for the contiguous United States, for the 2041-2070 time period with respect to the reference period of 1980-2000 (top). Color only (category 1) indicates that less than 50% of the models show a statistically significant change in the number of consecutive days. Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in the number of consecutive days, and more than 67% agree on the sign of the change (see text). Mean annual maximum number of consecutive days with T_{max} > 95°F for the 1980-2000 reference period (bottom left). Simulated mean annual maximum number of consecutive days with T_{max} > 95°F for the 2041-2070 future time period (bottom right). These are multi-model means from 8 NARCCAP regional climate simulations for the high (A2) emissions scenario. Note that top and bottom color scales are different. Increases are largest in the southwest U.S. and smallest in the north and areas of high elevation, with a pattern similar to the present-day climatology.

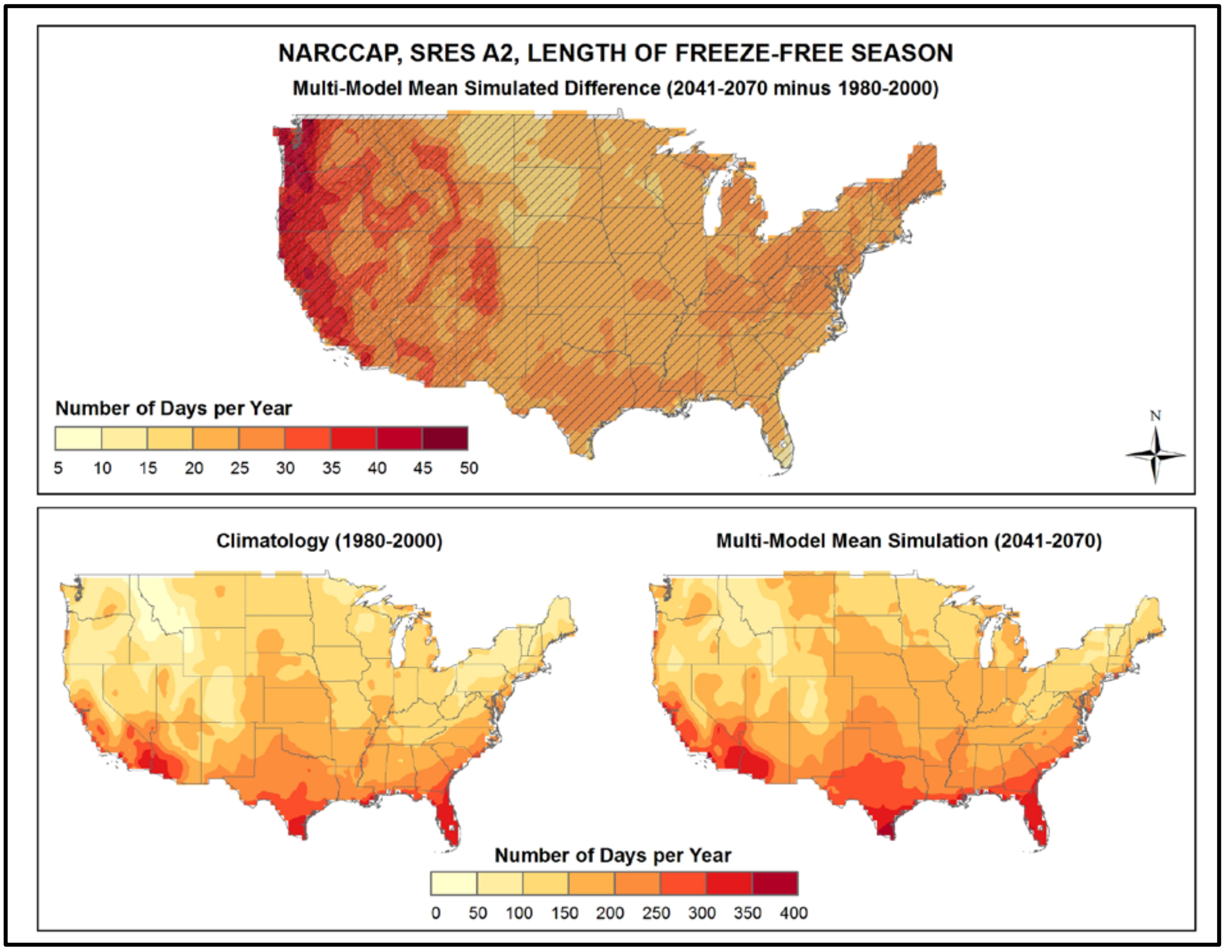

Figure 28. Simulated difference in the mean annual length of the freeze-free season for the contiguous United States, for the 2041-2070 time period with respect to the reference period of 1980-2000 (top). Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in the length of the freeze-free season, and more than 67% agree on the sign of the change (see text). Mean annual length of the freeze-free season for the 1980-2000 reference period (bottom left). Simulated mean annual length of the freeze-free season for the 2041-2070 future time period (bottom right). These are multi-model means from 8 NARCCAP regional climate simulations for the high (A2) emissions scenario. Note that top and bottom color scales are different. The length of the freeze-freeze season is simulated to increase throughout the U.S., with the greatest changes in the west.

Figure 29 shows the NARCCAP multi-model mean change in the average annual number of cooling degree days between 2055 and the model reference period of 1980-2000, for the high (A2) emissions scenario. In general, the changes are quite closely related to mean temperature with the warmest (coolest) areas showing the largest (smallest) changes. The hottest areas, such as southern Texas and Florida, are simulated to have the largest increase in the number of cooling degree days (CDDs) per year (up to 1,200 CDDs). The Northwest region has the smallest simulated increases, around 200 CDDs or less. The rest of the continental U.S. indicates between 200 and 1,000 more cooling degree days, with increasing values from north to south. The models indicate that the changes in cooling degree days across the U.S. are statistically significant. The models also agree on the sign of change, with all grid points satisfying category 3, i.e. the models are in agreement that the number of CDDs will increase under this scenario.

The NARCCAP multi-model mean change in the average annual number of heating degree days between 2055 and the model reference period of 1980-2000, for the high (A2) emissions scenario, is shown in Fig. 30. With the exception of Florida, the entire U.S. is simulated to experience a decrease of at least 400 heating degree days (HDDs) per year. The largest changes are simulated to occur in the high elevation areas of the Rockies, with decreases of up to 2,000 HDDs. The smallest decreases in heating degree days per year are simulated for the southeast region, along with Texas, Oklahoma, and parts of California and Arizona. The models once again indicate that the changes across the country are statistically significant. All grid points satisfy category 3, with the models also agreeing on the sign of change, i.e. the models are in agreement that the number of HDDs will decrease under this scenario.

3.6. Mean Precipitation

Figure 31 shows the spatial distribution of multi-model mean simulated differences in average annual precipitation for the three future time periods (2035, 2055, 2085) with respect to 1971-1999, for both emissions scenarios, for the 14 (B1) or 15 (A2) CMIP3 models. Spatially, there is a north-south gradient in precipitation changes. The southern Great Plains region shows the largest simulated decreases while the northern parts of the Midwest and Northeast regions show the greatest increases. This gradient increases in magnitude as time progresses for the high (A2) emissions scenario. The gradient in the low (B1) emissions scenario, however, is strongest for 2055 but moderates slightly by 2085. The largest north-south differences are for the A2 scenario in 2085, varying from increases of 6-9% in the far northeast to decreases of 9-12% in the far southwest and Texas. For the 2035 time period the changes in precipitation are not significant for most models (category 1) over the majority of grid points. This means that most models are in agreement that any changes will be smaller than the normal year-to-year variations that occur. By 2085, however, most models indicate changes that are larger than these normal variations (category 3) for northern areas in both scenarios and for the southwest in the A2 scenario. The models are mostly in agreement that precipitation will increase in the north and decrease in the southwest. By contrast, in parts of the central U.S., the models are in disagreement about the sign of the changes (category 2). This area of disagreement extends from northern California to the southeast U.S. in the A2 scenario for 2085.

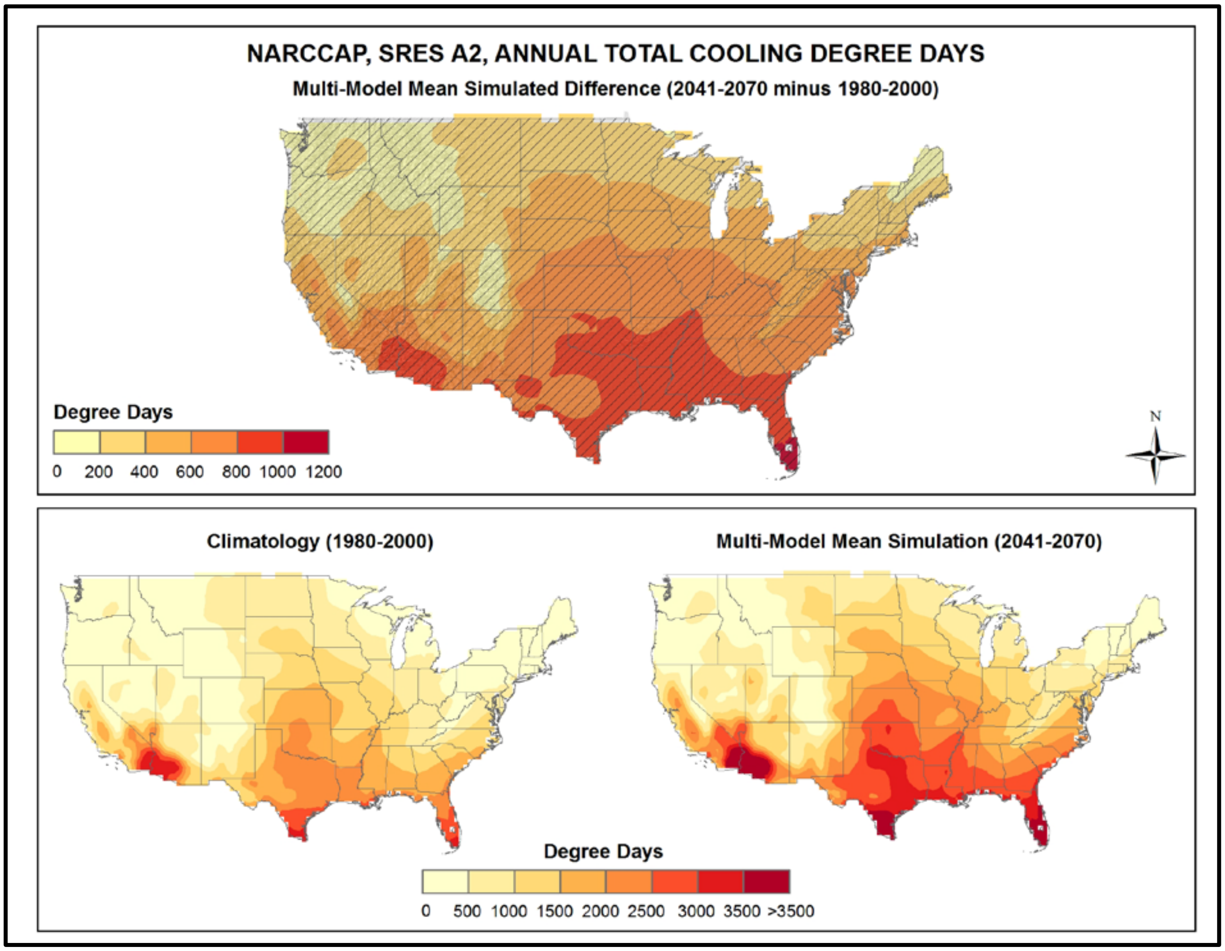

Figure 29. Simulated difference in the mean annual number of cooling degree days for the contiguous United States, for the 2041-2070 time period with respect to the reference period of 1980-2000 (top). Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in the number of cooling degree days, and more than 67% agree on the sign of the change (see text). Mean annual number of cooling degree days for the 1980-2000 reference period (bottom left). Simulated mean annual number of cooling degree days for the 2041-2070 future time period (bottom right). These are multi-model means from 8 NARCCAP regional climate simulations for the high (A2) emissions scenario. Note that top and bottom color scales are different. There are increases everywhere with the changes becoming larger from northwest to southeast.

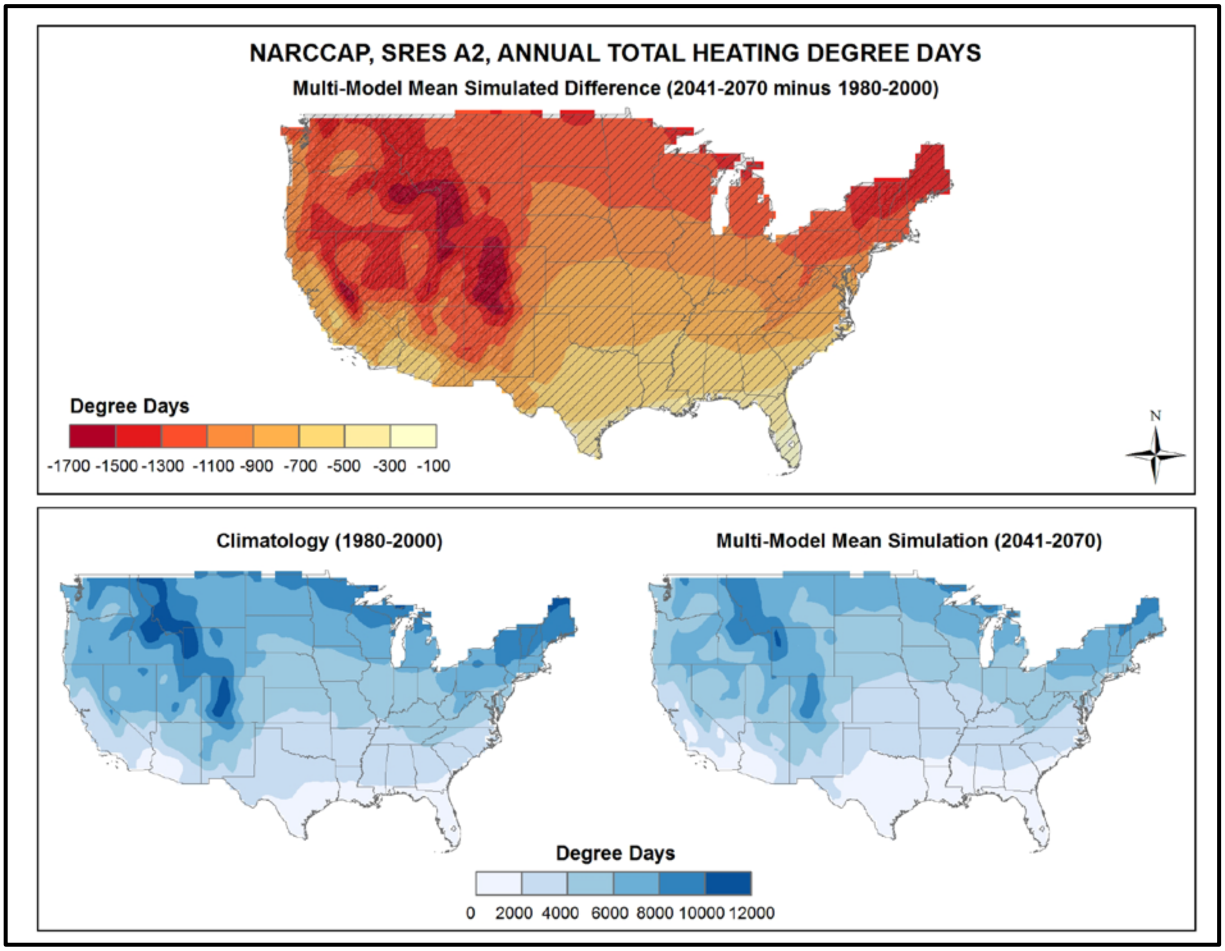

Figure 30. Simulated difference in the mean annual number of heating degree days for the contiguous United States, for the 2041-2070 time period with respect to the reference period of 1980-2000 (top). Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in the number of heating degree days, and more than 67% agree on the sign of the change (see text). Mean annual number of heating degree days for the 1980-2000 reference period (bottom left). Simulated mean annual number of heating degree days for the 2041-2070 future time period (bottom right). These are multi-model means from 8 NARCCAP regional climate simulations for the high (A2) emissions scenario. There are decreases everywhere with the largest changes in high elevation areas.

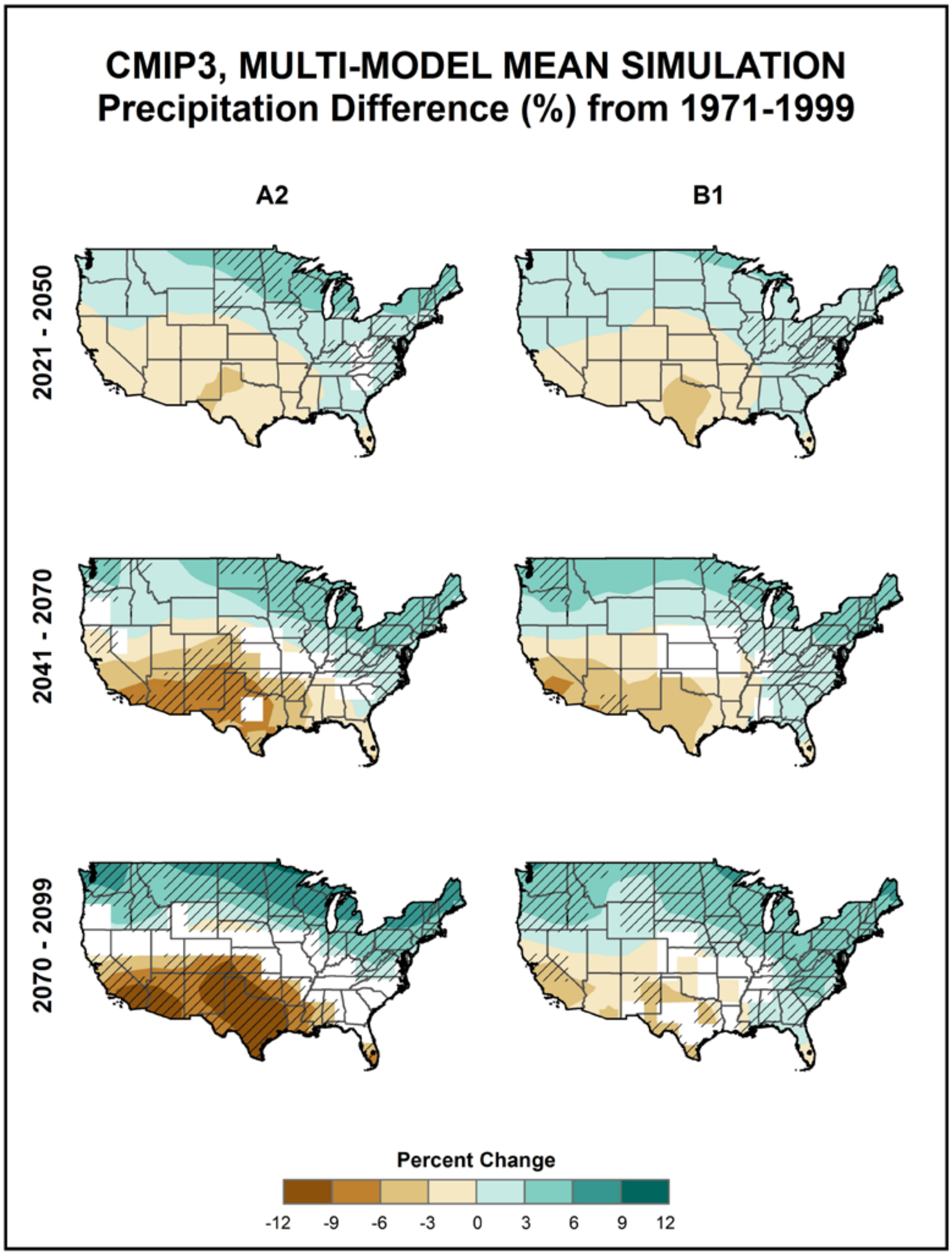

Figure 31. Simulated difference in annual mean precipitation (%) for the contiguous United States, for each future time period (2021-2050, 2041-2070, and 2070-2099) with respect to the reference period of 1971-1999. These are multi-model means for the high (A2) and low (B1) emissions scenarios from the 14 (B1) or 15 (A2) CMIP3 global climate simulations. Color only (category 1) indicates that less than 50% of the models show a statistically significant change in precipitation. Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in precipitation, and more than 67% agree on the sign of the change. Whited out areas (category 2) indicate that more than 50% of the models show a statistically significant change in precipitation, but less than 67% agree of the sign of the change (see text). Generally, the models simulate increases in the north and decreases in the south of the U.S.

Figure 32 shows the multi-model mean annual and seasonal 30-year average precipitation change between 2041-2070 and 1971-2000 for the high (A2) emissions scenario, for 11 NARCCAP regional climate model simulations. Regions of both positive and negative future changes in precipitation are simulated. The largest decreases are simulated to occur in west Texas as well as southern Arizona and New Mexico; the largest increases can be seen in the interior north. Winter changes exhibit the smallest spatial variations, ranging from -10 to +16% over the entire continental U.S. Changes are mostly upward for winter, but mostly downward in the summer. The largest variability also occurs in summer, ranging as high as +40% and as low as -48%.

The agreement between models was again assessed using the three categories described in Fig. 20. It can be seen that annually, and for all seasons, the simulated changes in precipitation are not statistically significant for most models over the majority of grid points (category 1). The models are in disagreement about the sign of change (category 2) for two small areas in northeastern Oregon for the annual simulation, as well as areas along the Gulf coast for summer, and portions of western Washington and southern California for the fall season. The models are in agreement in some areas, however, with statistically significant changes simulated by most models (category 3) in parts of the Midwest and Southeast U.S. for the annual simulation. The seasonal simulations also contain category 3 areas, most notably in parts of the upper Midwest for winter and spring.

Figure 33 shows the simulated change in annual mean precipitation for each future time period with respect to 1971-1999, for both emissions scenarios, averaged over the entire continental United States for the 14 (B1) or 15 (A2) CMIP3 models. In addition, averages for 9 of the NARCCAP simulations (relative to 1971-2000) and the 4 GCMs used in the NARCCAP experiment are shown for 2055 (A2 scenario only). Both the multi-model mean and individual model values are shown. While such large area averages mask all-important regional differences, this analysis illuminates the magnitude of inter-model differences and thus provides insights into the overall uncertainties of the simulations. All the multi-model mean simulated changes in precipitation are close to zero for the high (A2) emissions scenario and slightly positive for B1. The mean of the NARCCAP simulations is slightly greater than the mean of the CMIP3 GCMs (+2% compared to 0%), but close to the mean of the 4 GCMs used to drive the NARCCAP simulations. The inter-model range of individual model changes in Fig. 33 is large compared to the differences in the multi-model means. In fact, for both emissions scenarios, the individual model range is much larger than the differences in the CMIP3 multi-model means between time periods.

Figure 34 shows the simulated change in seasonal mean precipitation for each future time period with respect to 1971-1999, for the high (A2) emissions scenario, averaged over the entire continental U.S. for the 15 CMIP3 models, as well as the NARCCAP models for 2055, relative to 1971-2000. Again, both the multi-model mean and individual model values are shown. Multi-model mean decreases are simulated to occur in summer, ranging from -3% in 2035 to -8% in 2085. The other seasons are simulated to see increases in precipitation of up to 6%. The NARCCAP models, which are displayed for 2055, simulate changes in precipitation that are slightly greater in magnitude than those of the CMIP3 models for all four seasons. As was the case for the annual totals in Fig. 33, the model ranges in Fig. 34 are large compared to the multi-model mean differences. This illustrates the large uncertainty in the precipitation estimates using these simulations.

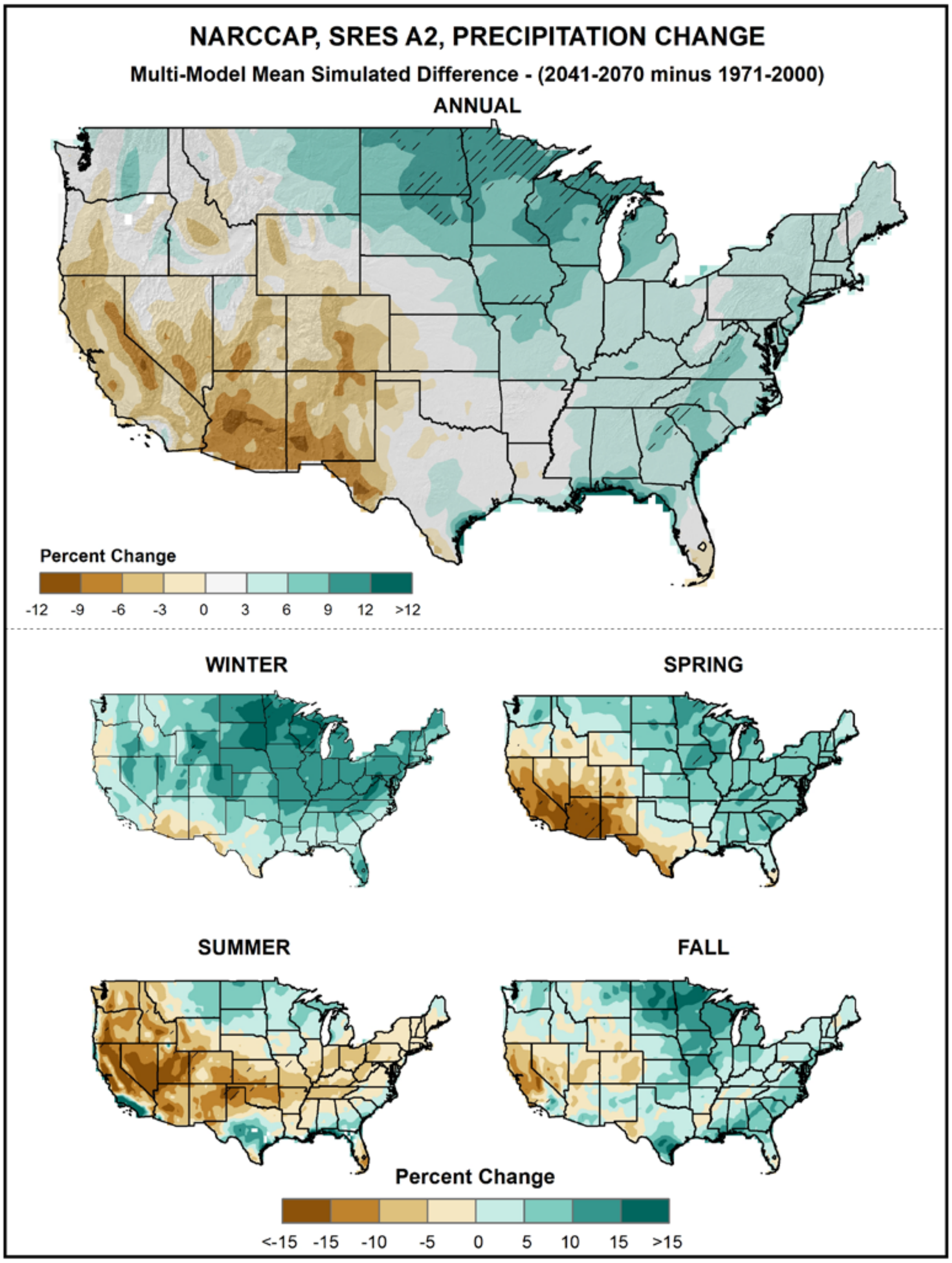

Figure 32. Simulated difference in annual and seasonal mean precipitation (%) for the contiguous United States, for 2041-2070 with respect to the reference period of 1971-2000. These are multi-model means from 11 NARCCAP regional climate simulations for the high (A2) emissions scenario. Color only (category 1) indicates that less than 50% of the models show a statistically significant change in precipitation. Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in the number of days, and more than 67% agree on the sign of the change Whited out areas (category 2) indicate that more than 50% of the models show a statistically significant change in precipitation, but less than 67% agree of the sign of the change (see text). Note that top and bottom color scales are unique, and different from that of Fig. 31. The annual change is upward in the northern and eastern U.S. and downward in the southwest. Changes are mostly upward in winter, spring, and fall, and downward in summer.

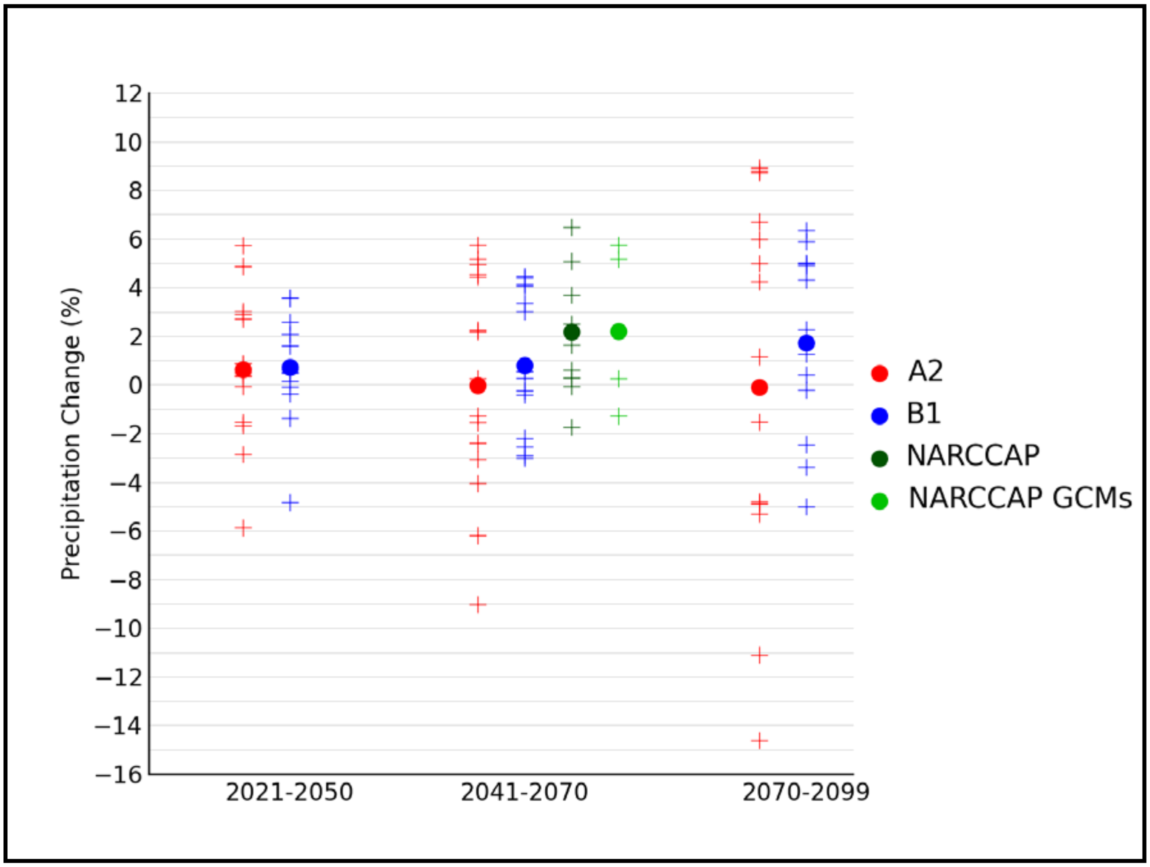

Figure 33. Simulated annual mean precipitation change (%) for the contiguous United States, for each future time period (2021-2050, 2041-2070, and 2070-2099) with respect to the reference period of 1971-1999. Values are given for the high (A2) and low (B1) emissions scenarios for the 14 (B1) or 15 (A2) CMIP3 models. Also shown for 2041-2070 (high emissions scenario only) are values (relative to 1971-2000) for 9 NARCCAP models, as well as for the 4 GCMs used to drive the NARCCAP simulations. The small plus signs (+) indicate each individual model and the circles depict the multi-model means. The range of model-simulated changes is very large compared to the mean changes and to differences between the A2 and B1 scenarios.

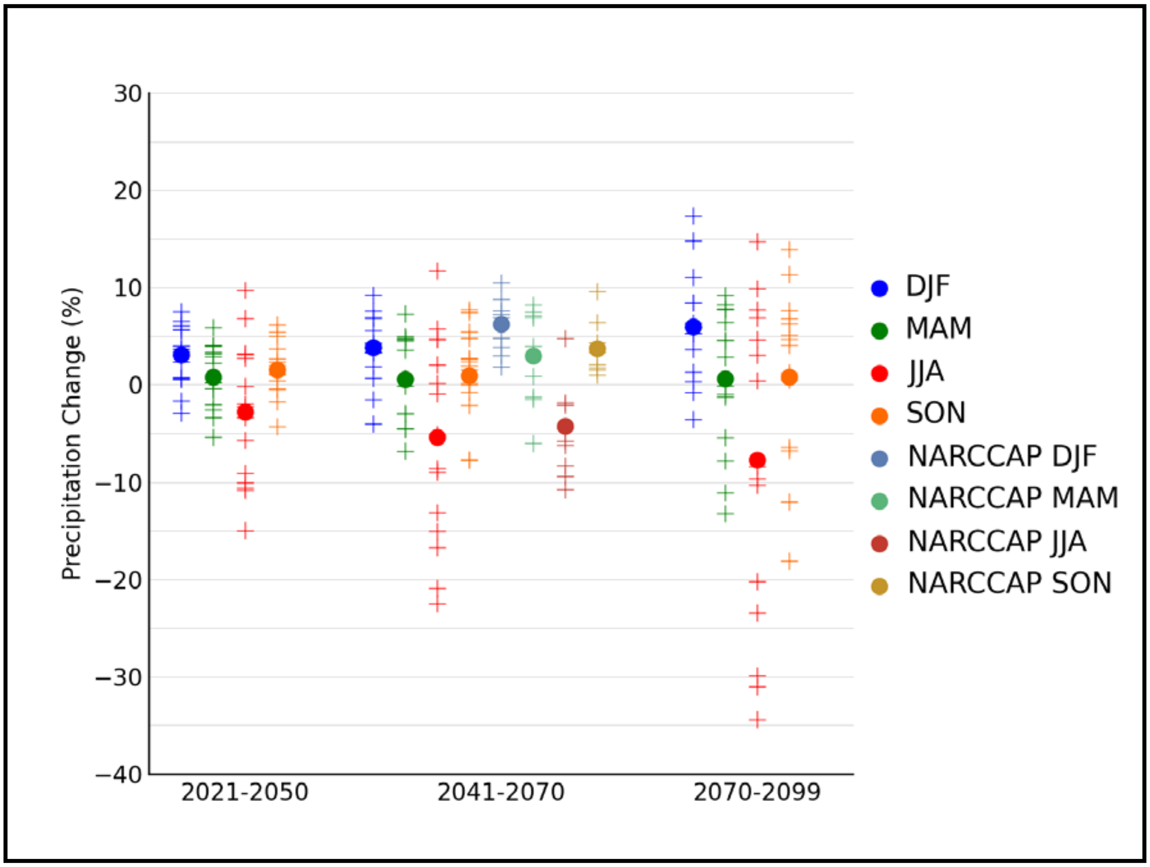

Figure 34. Simulated seasonal mean precipitation change (%) for the contiguous United States, for each future time period (2021-2050, 2041-2070, and 2070-2099) with respect to the reference period of 1971-1999. Values are given for all 15 CMIP3 models for the high (A2) emissions scenario. Also shown are values (relative to 1971-2000) for 9 NARCCAP models for 2041-2070. The small plus signs (+) indicate each individual model and the circles depict the multi-model means. Seasons are indicated as follows: winter (DJF, December-January-February), spring (MAM, March-April-May), summer (JJA, June-July-August), and fall (SON, September-October-November). The range of model-simulated changes is large compared to the mean changes and to differences between the seasons.

3.7. Extreme Precipitation

Figure 35 shows the spatial distribution of the multi-model mean change in the average annual number of days with precipitation exceeding 1 inch, for 8 NARCCAP regional climate model simulations. Again this is the difference between the period of 2041-2070 and the 1980-2000 model reference period, for the high (A2) emissions scenario. In addition to this difference map, maps of the model simulations of the actual values for historical conditions (NARCCAP models driven by the NCEP Reanalysis II) and for the future are also displayed for comparison. As described in the climatology section, the frequency of such extreme precipitation events has been seen to increase throughout the U.S. since 1991. Most areas are simulated to have further increases, particularly portions of the north central U.S. and intermountain west. Decreases are simulated for some areas, such as northern California, eastern Colorado, southern Arizona and southwestern New Mexico, but these values are minimal. The largest simulated changes in extreme precipitation occurrences, of more than 50%, are located to the west of the Rockies. Changes in the number of days with precipitation of more than 1 inch are not statistically significant for most models (category 1) over the majority of grid points. This means that most models are in agreement that any changes will be smaller than the normal year-to-year variations that occur under this scenario. However, for grid points in some areas (such as portions of the Midwest and Northeast) most models indicate statistically significant changes (category 3). In a few small areas in southern Arizona the models are in disagreement about the sign of the changes (category 2).

Consecutive days with little or no precipitation can reduce soil moisture levels and put stress on plants. Figure 36 shows the NARCCAP multi-model mean change in the average annual maximum number of consecutive days with precipitation less than 0.1 inches (3 mm) between 2055 and the model reference period of 1980-2000, for the high (A2) emissions scenario. An increase in the number of days with little or no precipitation is simulated for areas that are already prone to little precipitation. Increases of up to 25 days per year are simulated for parts of southern California and Arizona. The northern Great Plains and Midwest are simulated to see small decreases or no change over time, with the majority of the country seeing simulated increases of up to 15 days. Changes in the number of consecutive days with precipitation of less than 0.1 inches are not statistically significant for most models (category 1) over the majority of grid points in the north and east of the U.S. This means that most models are in agreement that any changes will be smaller than the normal year-to-year variations that occur under this scenario. However, in southern and western areas, where large increases are simulated, most models indicate changes that are larger than these normal variations (category 3). This is also the case in the northern Midwest and Great Plains, where the largest simulated decreases are seen. The models are in disagreement about the sign of changes category 2) for several grid points scattered across the U.S.

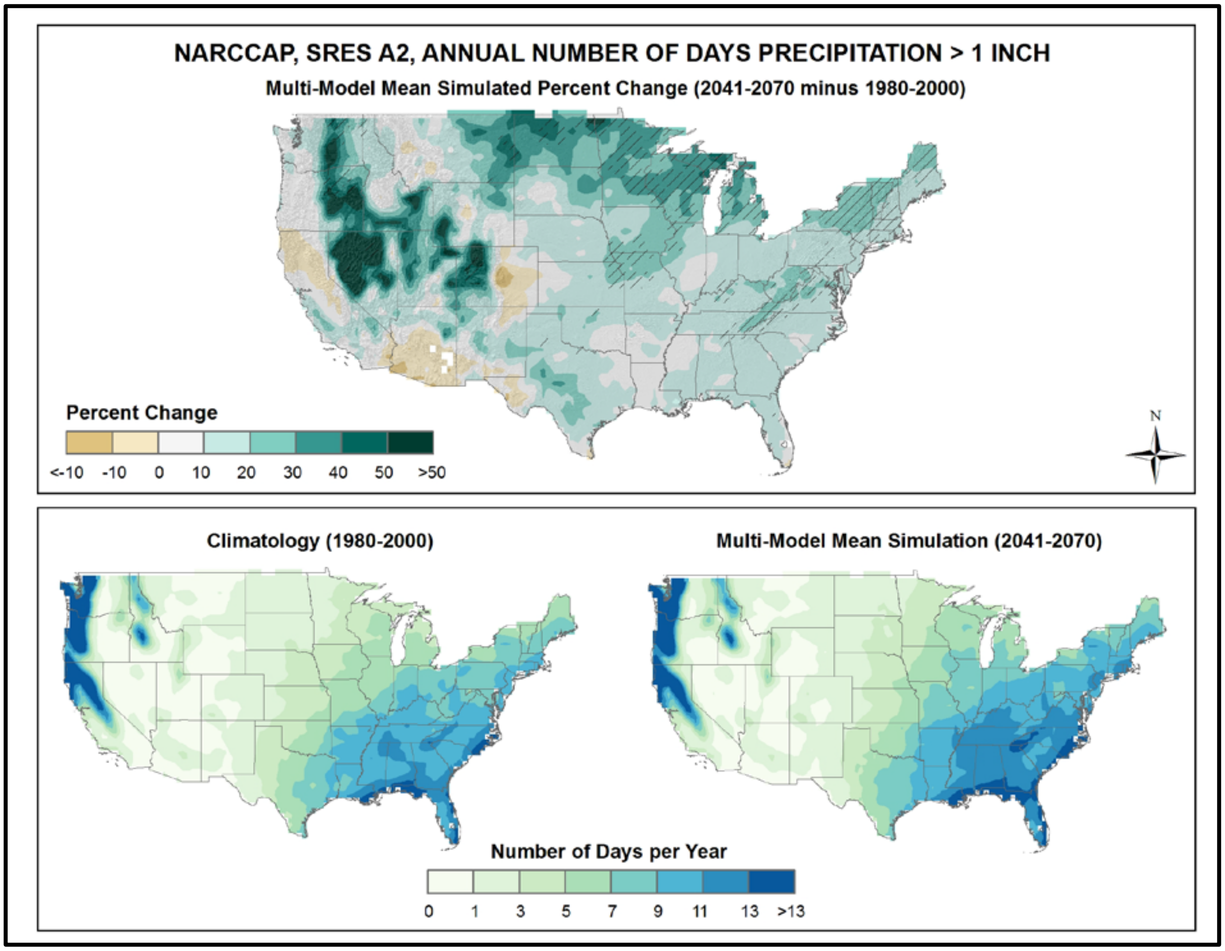

Figure 35. Simulated percentage difference in the mean annual number of days with precipitation of greater than one inch for the contiguous United States, for the 2041-2070 time period with respect to the reference period of 1980-2000 (top). Color only (category 1) indicates that less than 50% of the models show a statistically significant change in the number of days. Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in the number of days, and more than 67% agree on the sign of the change. Whited out areas (category 2) indicate that more than 50% of the models show a statistically significant change in the number of days, but less than 67% agree of the sign of the change (see text). Mean annual number of days with precipitation of greater than one inch for the 1980-2000 reference period (bottom left). Simulated mean annual number of days with precipitation of greater than one inch for the 2041-2070 future time period (bottom right). These are multi-model means from 8 NARCCAP regional climate simulations for the high (A2) emissions scenario. The models simulate decreases in parts of the southwest U.S., with increases across the remainder of the region.

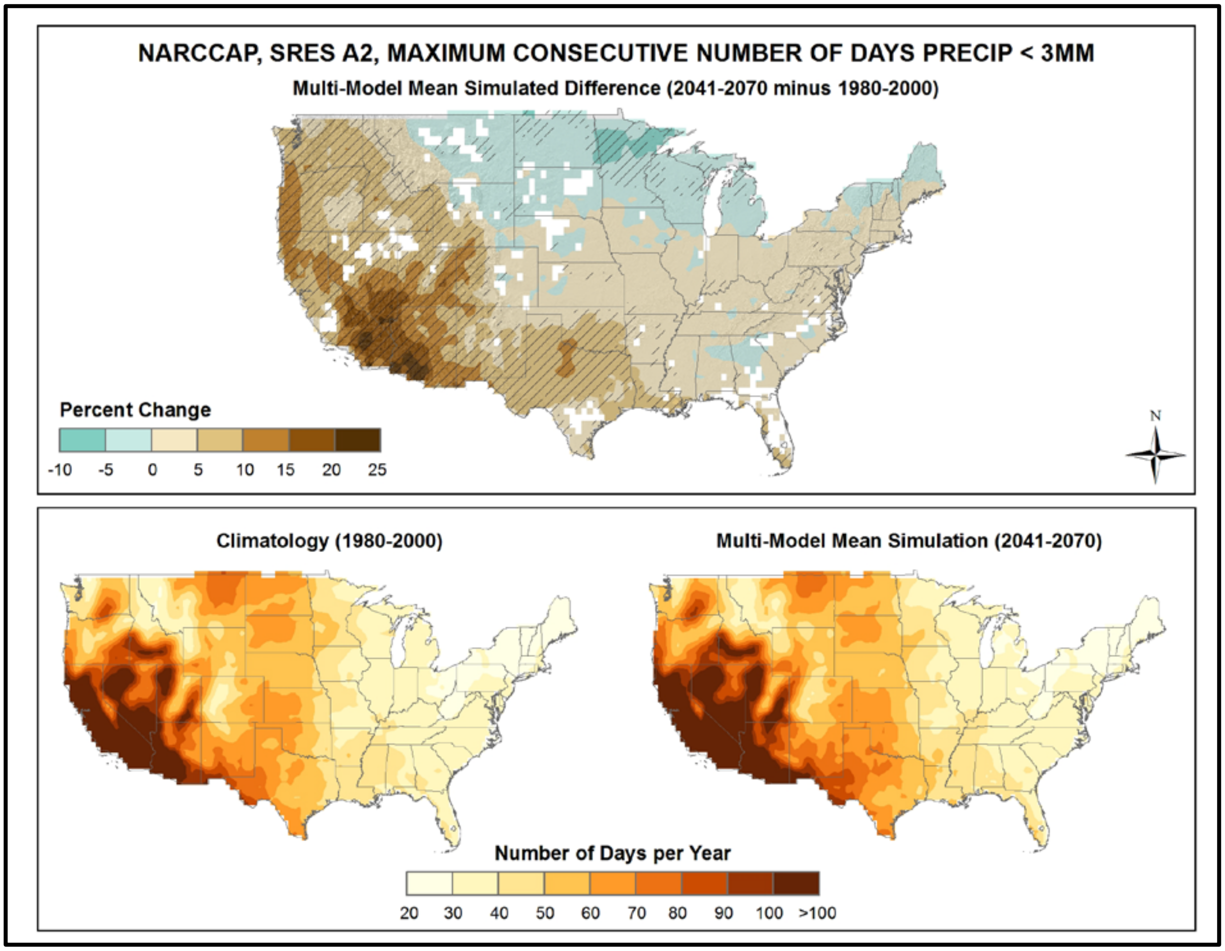

Figure 36. Simulated difference in the mean annual maximum number of consecutive days with precipitation of less than 0.1 inches/3 mm for the contiguous United States, for the 2041-2070 time period with respect to the reference period of 1980-2000 (top). Color only (category 1) indicates that less than 50% of the models show a statistically significant change in the number of consecutive days. Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in the number of consecutive days, and more than 67% agree on the sign of the change. Whited out areas (category 2) indicate that more than 50% of the models show a statistically significant change in the number of consecutive days, but less than 67% agree of the sign of the change (see text). Mean annual maximum number of consecutive days with precipitation of less than 0.1 inches/3 mm for the 1980-2000 reference period (bottom left). Simulated mean annual maximum number of consecutive days with precipitation of less than 0.1 inches/3 mm for the 2041-2070 future time period (bottom right). These are multi-model means from 8 NARCCAP regional climate simulations for the high (A2) emissions scenario. The models simulate increases over the majority of the U.S., with the greatest changes in the southwest.

3.8. Comparison Between Model Simulations and Observations

In this section, some selected comparisons between CMIP3 model simulations and observations are presented. These are limited to annual and seasonal temperature and precipitation. The model simulations of the 20th century that are shown herein are based on estimated historical forcings of the climate systems, including such factors as greenhouse gases, volcanic eruptions, solar variations, and aerosols. Also shown are the simulations of the 21st century for the high (A2) emissions scenario.

In these comparisons, both model and observational data are expressed as deviations from the 1901-1960 average. As explained in Section 2.4 (Climatic Trends), acceleration of the anthropogenic forcing occurs shortly after 1960. Thus, for the purposes of comparing net warming between periods of different anthropogenic forcing, 1960 is a rational choice for the ending date of a reference period. It is not practical to choose a beginning date earlier than about 1900 because many model simulations begin in 1900 or 1901 and the uncertainties in the observational time series increase substantially prior to 1900. Therefore, the choice of 1901-1960 as the reference period is well suited for this purpose (comparing the net warming between periods of different anthropogenic forcing). However, there are some uncertainties in the suitability of the 1901-1960 reference period for this purpose. Firstly, there is greater uncertainty in the natural climate forcings (e.g., solar variations) during this time period than in the latter half of the 20th century. If there are sizeable errors in the estimated natural forcings used in climate models, then the simulations will be affected; this type of error does not represent a model deficiency. Secondly, the 1930s “Dust Bowl” era is included in this period. The excessive temperatures experienced then, particularly during the summers, are believed to be caused partially by poor land management through its effects on the surface energy budget. Climate models do not incorporate land management changes and there is no expectation that models should simulate the effects of such. Thirdly, there are certain climate oscillations that occur over several decades. These oscillations have important effects on regional temperatures. A 60-year period is too short to sample entire cycles of some of these, and thus only represents a partial sampling of the true baseline climate.

Figure 37 shows observed (using the same data set as shown in Fig. 8) and simulated decadal mean annual temperature changes for the contiguous United States from 1900 to 2100, expressed as deviations from the 1901-1960 average. The observed temperature values are mostly contained within the envelope of 20th century modeled temperatures, except for the 1930s which are slightly warmer than the warmest model and the 1970s which are slightly cooler than the coolest model shown.

The behavior for the four seasons (Fig. 38) is generally similar. In particular, for winter, spring, and fall, the observations are generally within the envelope of the model simulations. For the summer season (Fig. 38, lower left), observed temperatures for the 1930s are higher than any model simulation and the observed temperatures for the 1990s are lower than any model simulation. As a result, the observed temperature trend is upward and statistically significant but the trend magnitude is lower than any individual model. Regional time series (not shown) indicate that this reduced summer warming was pronounced in central and southeast sections. This feature is well known and has been dubbed the “warming hole”. Research on the causes of this feature is active and ongoing.

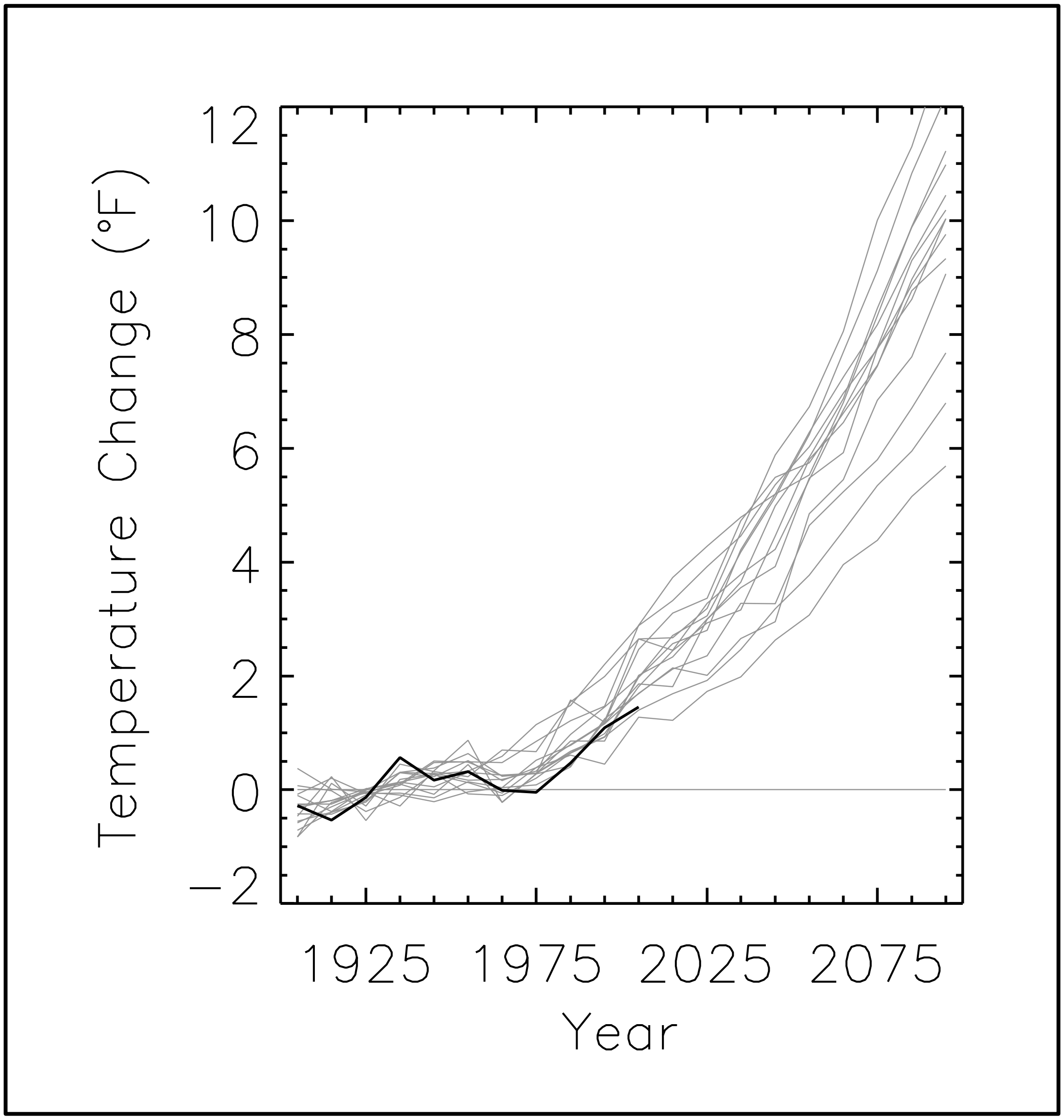

Figure 37. Observed decadal mean annual temperature change (deviations from the 1901-1960 average, °F) for the contiguous United States (black line). Based on a new gridded version of COOP data from the National Climatic Data Center, the CDDv2 data set (R. Vose, personal communication, July 27, 2012). Gray lines indicate the 20th and 21st century simulations from 15 CMIP3 models, for the high (A2) emissions scenario. The observed amount of 20th century warming is within the envelope of model simulations.

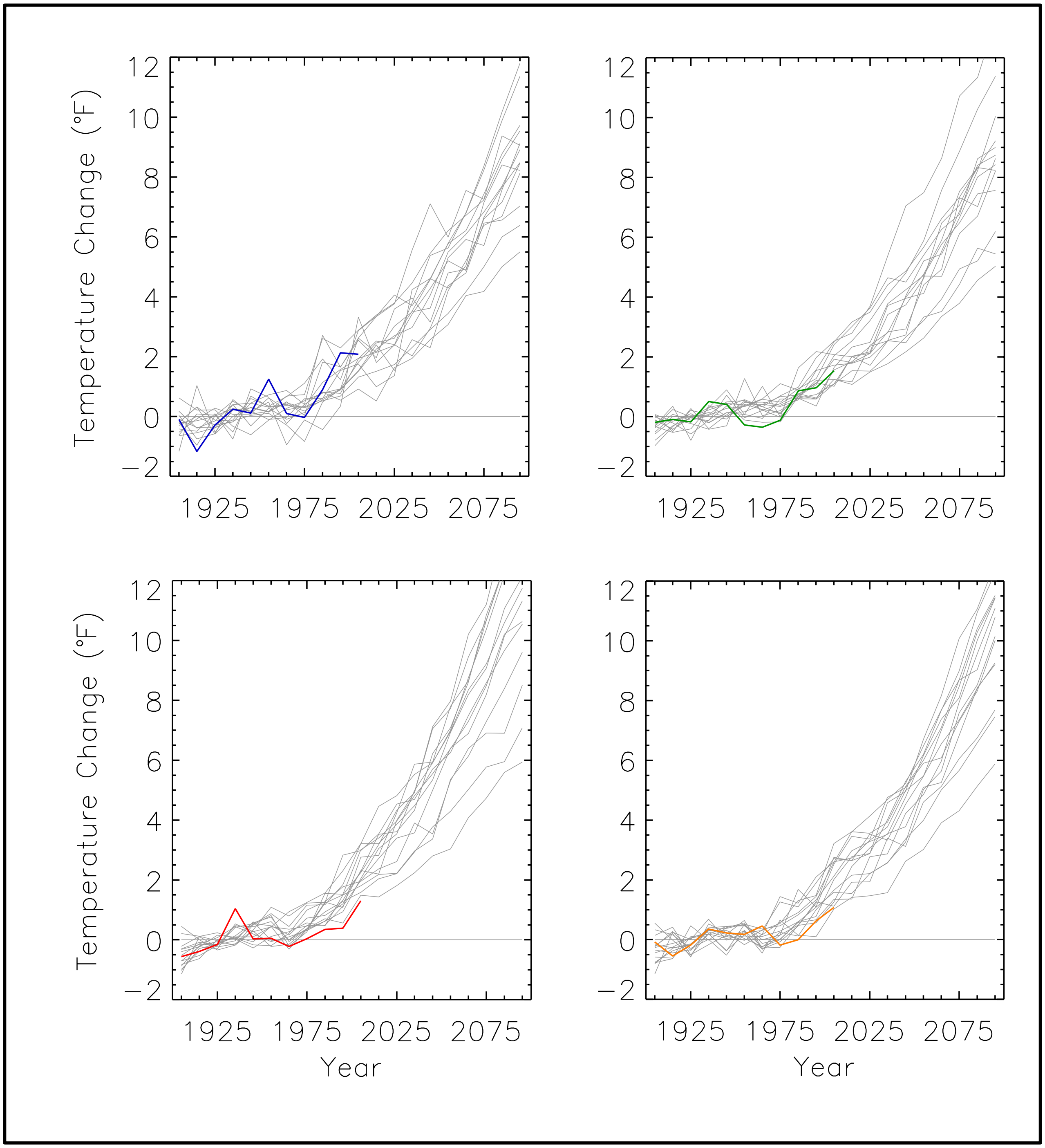

Figure 38. Observed decadal mean temperature change (deviations from the 1901-1960 average, °F) for the contiguous United States for winter (top left, blue line), spring (top right, green line), summer (bottom left red line), and fall (bottom right, orange line). Based on a new gridded version of COOP data from the National Climatic Data Center, the CDDv2 data set (R. Vose, personal communication, July 27, 2012). Gray lines indicate 20th and 21st century simulations from 15 CMIP3 models, for the high (A2) emissions scenario. The observed amount of 20th century warming is generally within the envelope of model simulations.

The 21st century portions of the time series indicate that the simulated future warming is much larger the observed and simulated temperature changes for the 20th century.

Observed and model-simulated decadal mean precipitation changes (using the same data set as shown in Fig. 9) can be seen in Fig. 39 for annual and Fig. 40 for seasonal values. The observed variability is generally greater than the model simulations. This leads to a number of individual observed decadal values being outside the envelope of the model simulations. This is particularly true of the fall where there are a few very large observed anomalies that are well outside the envelope of the model simulations. The dry anomalies of the 1930s Dust Bowl era in the annual and summer time series are well outside the envelope of the model simulations. The 21st century portions of the time series show increased variability among the model simulations. It can be seen that the majority of the models simulate an overall increase in precipitation for winter, while many models simulate large decreases for summer.

On decadal time scales, climate variations arising from natural factors can be comparable to or larger than changes arising from anthropogenic forcing. An analysis of change on such time scales was performed by examining the decadal changes simulated by the CMIP3 models with respect to the most recent historical decade of 2001-2010. Figure 41 shows the simulated change in decadal mean values of annual temperature for each future decadal time period with respect to the most recent historical decade of 2001-2010, averaged over the entire continental U.S. for the 14 (B1) or 15 (A2) CMIP3 models. For the 2011-2020 decade, the temperature increases are not statistically significant relative to the 2001-2010 decade for several models. As the time period progresses, more of the individual models simulate statistically significant temperature changes, with all being significant at the 95% confidence level by 2035 for the A2 scenario and 2055 for the B1 scenario. All the model decadal mean values lie outside the 10-90th percentile range of the historical annual temperature anomalies by 2045 for the A2 scenario and 2055 for the B1 scenario. As also shown in Fig. 37, the model simulations show increased variability over time, with the inter-model range of temperature changes for 2091-2100 being more than double that for 2051-2060 (for the high emissions scenario).

The corresponding simulated change in decadal mean values of annual precipitation can be seen in Fig. 42. Unlike for temperature, many of the model values of precipitation change are not statistically significant in all decades out to 2091-2099. There is also no great difference between the high and low emissions scenarios. Once again, variability in the model simulations becomes greater over time, with a larger number of models lying outside the 10-90th percentile range for each increasing time period.

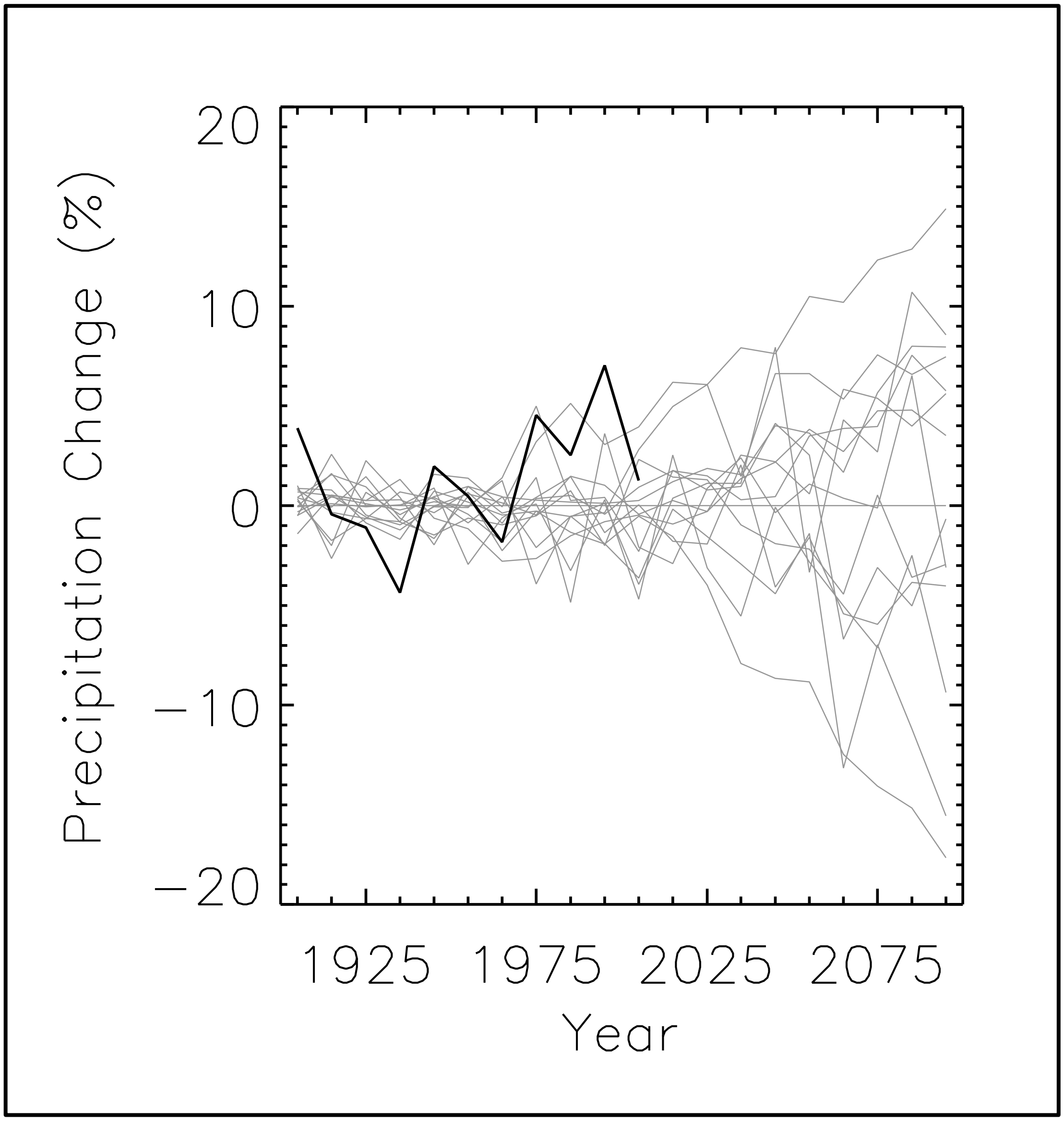

Figure 39. Observed decadal mean annual precipitation change (deviations from the 1901-1960 average, %) for the contiguous United States (black line). Based on a new gridded version of COOP data from the National Climatic Data Center, the CDDv2 data set (R. Vose, personal communication, July 27, 2012). Gray lines indicate the 20th and 21st century simulations from 15 CMIP3 models, for the high (A2) emissions scenario. Observed precipitation variations are greater than the variations in the model simulations.

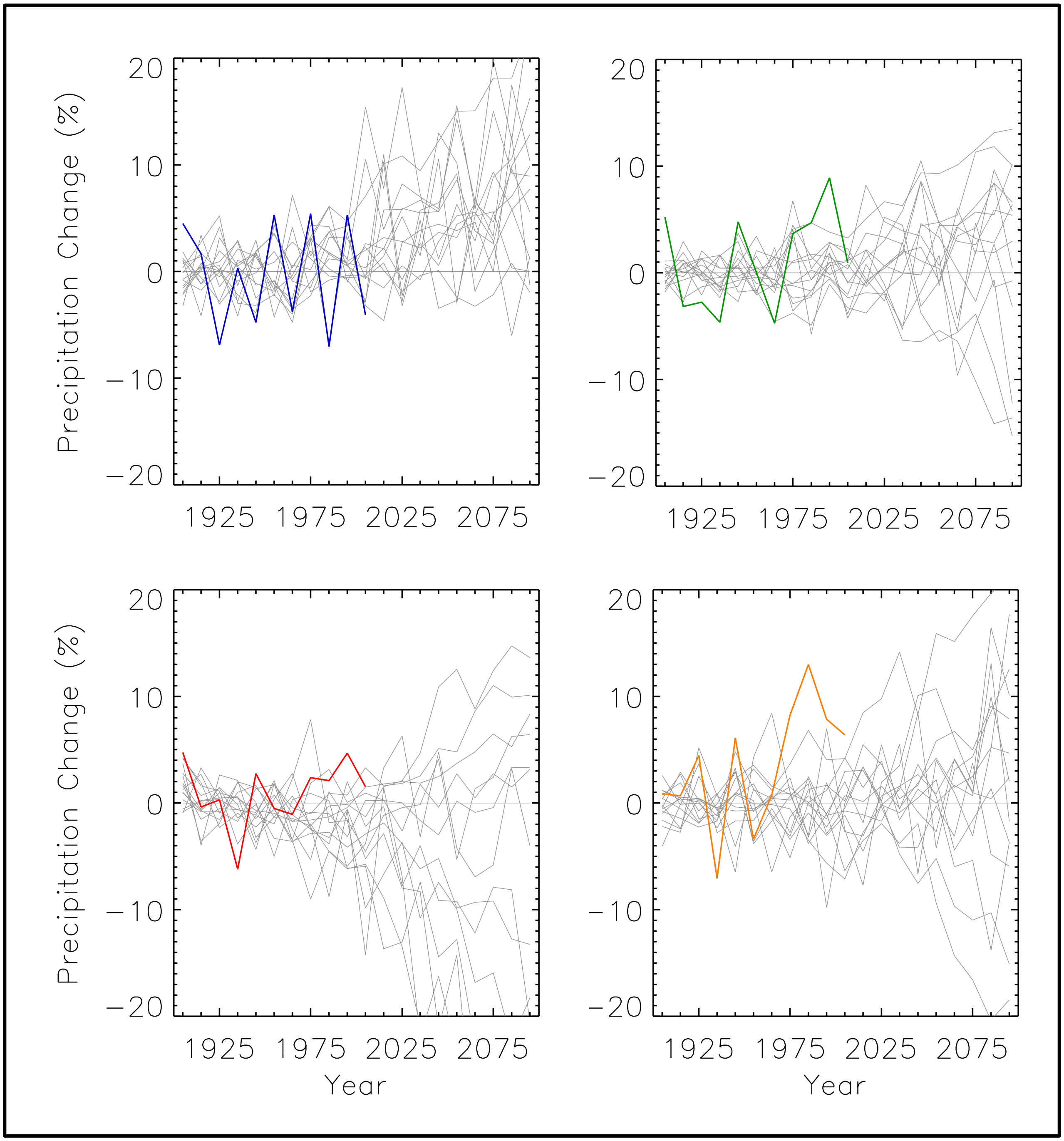

Figure 40. Observed decadal mean precipitation change (deviations from the 1901-1960 average, %) for the contiguous United States for winter (top left, blue line), spring (top right, green line), summer (bottom left red line), and fall (bottom right, orange line Based on a new gridded version of COOP data from the National Climatic Data Center, the CDDv2 data set (R. Vose, personal communication, July 27, 2012). Gray lines indicate 20th and 21st century simulations from 15 CMIP3 models, for the high (A2) emissions scenario. Observed seasonal precipitation variations are greater than variations of the model simulations for all seasons.

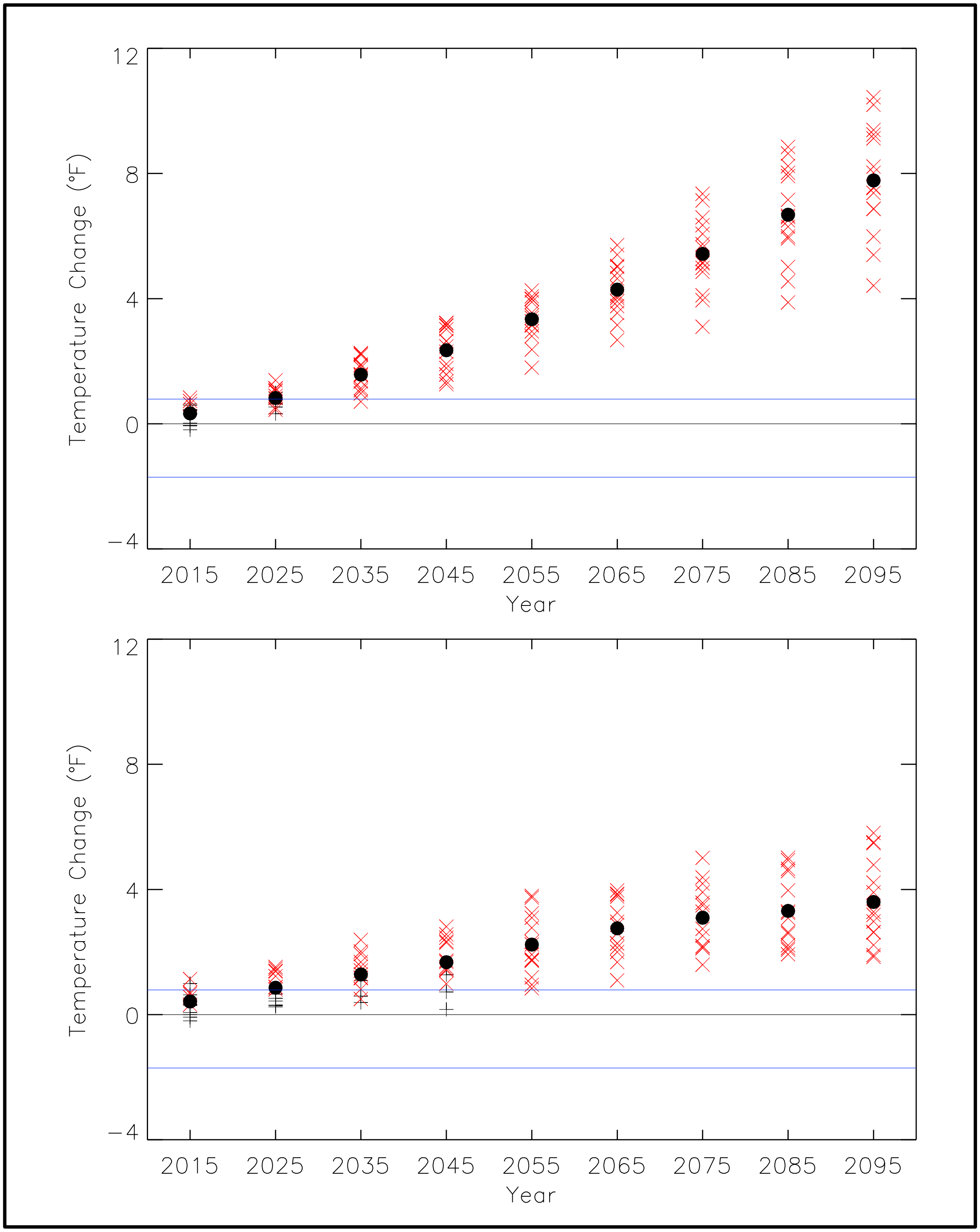

Figure 41. Simulated decadal mean change in annual temperature (°F) for the contiguous United States for each future decadal time period (represented by their approximate midpoints, e.g., 2015 = 2011-2020), with respect to the reference period of 2001-2010. Values are given for the high (A2, top) and low (B1, bottom) emissions scenarios for the 14 (B1) or 15 (A2) CMIP3 models. Large circles depict the multi-model means. Each individual model is represented by a black plus sign (+), or a red x if the value is statistically significant at the 95% confidence level. Blue lines indicate the 10th and 90th percentiles of 30 annual anomaly values from 1981-2010.

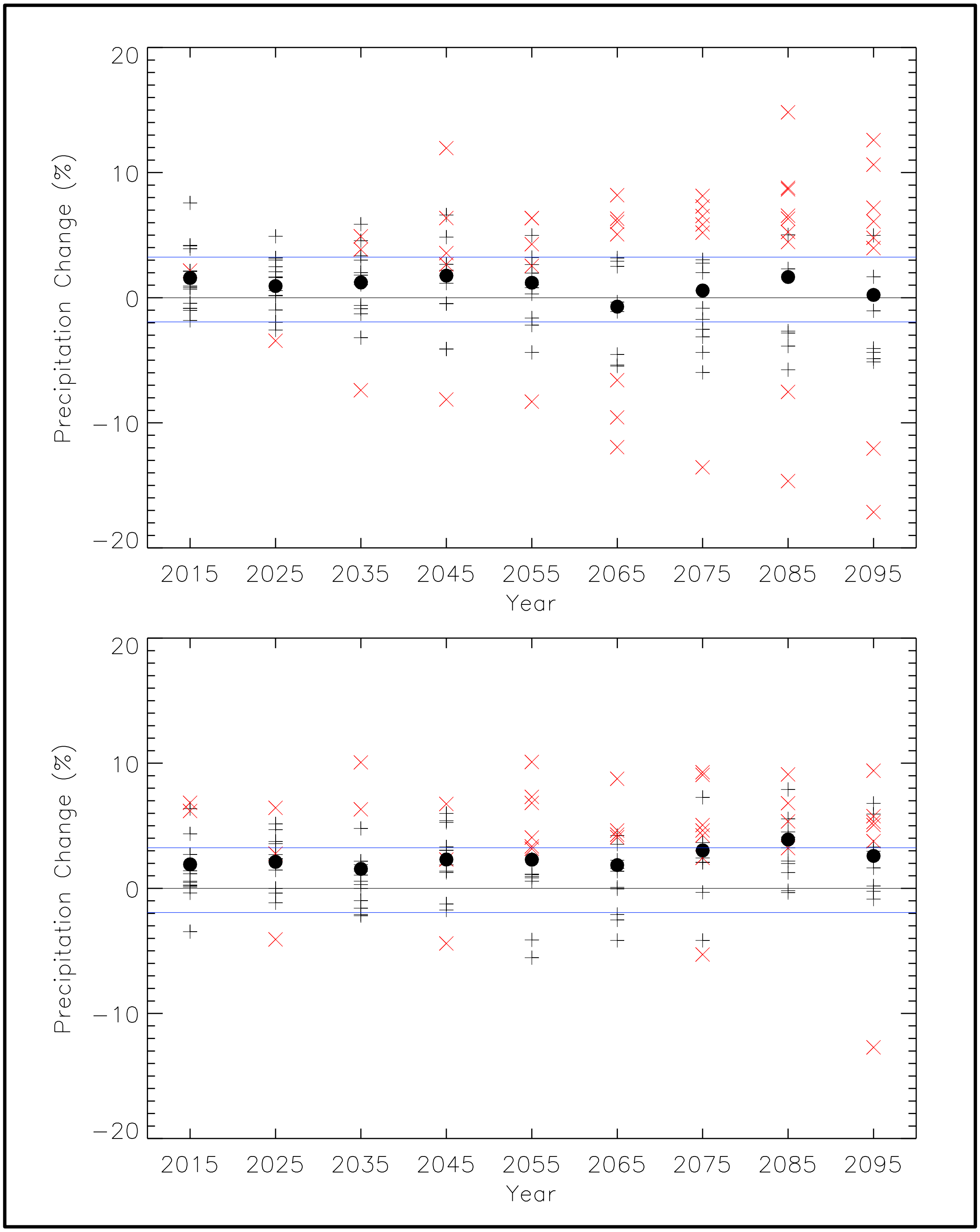

Figure 42. Simulated decadal mean change in annual precipitation (%) for the contiguous United States for each future decadal time period (represented by their approximate midpoints, e.g., 2015 = 2011-2020), with respect to the reference period of 2001-2010. Values are given for the high (A2, top) and low (B1, bottom) emissions scenarios for the 14 (B1) or 15 (A2) CMIP3 models. Large circles depict the multi-model means. Each individual model is represented by a black plus sign (+), or a red x if the value is statistically significant at the 95% confidence level. Blue lines indicate the 10th and 90th percentiles of the 30 annual anomaly values from 1981-2010.

4. SUMMARY

The primary purpose of this document is to provide physical climate information for potential use by the authors of the 2013 National Climate Assessment report. The document contains two major sections. One section summarizes historical conditions in the U.S. The description of the historical climate focuses primarily on trends in temperature and precipitation metrics that are important in the region. The core data set used is that of the National Weather Service's Cooperative Observer Network (COOP).

The second section summarizes climate model simulations for two scenarios of the future path of greenhouse gas emissions, the IPCC SRES high (A2) and low (B1) emissions scenarios. These simulations incorporate analyses from multiple sources, the core source being Climate Model Intercomparison Project 3 (CMIP3) simulations. Additional sources consist of statistically- and dynamically-downscaled data sets, including simulations from the North American Regional Climate Change Assessment Program (NARCCAP). Analyses of the simulated future climate are provided for the periods of 2021-2050, 2041-2070, and 2070-2099, with changes calculated with respect to an historical climate reference period (1971-1999, 1971-2000, or 1980-2000). The resulting climate conditions are to be viewed as scenarios, not forecasts, and there are no explicit or implicit assumptions about the probability of occurrence of either scenario. The basis for these climate scenarios (emissions scenarios and sources of climate information) were considered and approved by the National Climate Assessment Development and Advisory Committee.

Some key characteristics of the historical climate include:

- Climatic phenomena that have major impacts on the U.S. include: heavy rainfall and floods, drought, extreme heat and cold, winter storms (in northern regions), severe thunderstorms and tornadoes, and tropical cyclones.
- The U.S. as a whole has experienced statistically significant warming since 1895 in all seasons. This warming has not been uniform in space. Warming has been greatest in the west and north. By contrast, the southeast has not experienced any overall warming, one of the few regions globally not to exhibit an overall warming trend in surface temperature over the 20th century (IPCC 2007a). This "warming hole" also includes parts of the Great Plains and Midwest regions in the summer.
- Temperatures increased rapidly in the early part of the 20^{th} century, then decreased slightly during the middle of the 20^{th} century. Since about 1980, temperatures have been increasing.
- The number of extreme hot spells has tended to increase since a minimum in the 1960s, such that the 2000s experienced the 2^{nd} highest number of any decade. The decade of the 1930s remains the highest. Recent increases in hot spells are greatest in the western and northeastern regions. The number of extreme cold spells has decreased since a peak in the 1980s. The 2000s had the smallest number of any decade since 1895, the beginning year of our analysis.
- There have been statistically significant upward trends in annual and fall precipitation. Trends in other seasons are not statistically significant.
- A national upward trend in the number of extreme precipitation events is highly statistically significant. The 2000s experienced the greatest number of such extremes. Regionally, this

upward trend is prominent in the eastern regions, while far western regions have not experienced an overall trend.

- The length of the freeze-freeze season has increased by about 2 weeks since 1900. The increase has been greater in the western U.S. than in the eastern U.S.
- Lakes with long-term ice cover records show sizeable decreases in ice cover area and duration.

The climate characteristics simulated by climate models for the two emissions scenarios have the following key features:

- Both the CMIP3 and NARCCAP simulations indicate that spatial variations in temperature increase are relatively small, with the greatest temperature increases simulated in the interior and the least in coastal regions. The CMIP3 models indicate that temperature increases across the entire contiguous U.S. are statistically significant (for all three future time periods and both emissions scenarios).
- Temperature increases are simulated to be similar in magnitude for the high and low emissions scenarios for the near future, whereas late in the 21st century the high emissions scenario indicates approximately double the amount of warming.
- The range of model-simulated temperature changes is substantial, indicating substantial uncertainty in the magnitude of warming associated with each scenario. However, in each model simulation, the warming is unequivocal and large compared to historical variations. This is also true for all of the derived temperature variables described below.
- NARCCAP model simulations indicate increases in the number of days with a maximum temperature of more than 95°F, from more than 35 days in the southeast and southwest to less than 5 in the far north. The number of consecutive warm days is simulated to increase the most in the south-central and southwest areas (for the A2 scenario at mid-century).
- The number of days with minimum temperatures below 10°F is simulated to decrease across the U.S. by mid-century in the A2 scenario. The largest decreases of more than 20 days are simulated in the far north and mountain regions. The area of near zero days expands considerably. The number of days below 32°F are simulated to decrease by more than 20 days across much of the central and northern U.S.
- Increases in the length of the freeze-free season are in the range of 20 to 30 days across most of the U.S. with larger decreases of up to 50 days in portions of the far west (for the A2 scenario at mid-century).
- Cooling degree days increase by more than 800 in the southeast and southwest, with smaller increases to the north; the increases everywhere represent large percentage changes. Correspondingly, heating degree days are simulated to decrease by less than 500 in the south to more than 1,300 in the far north and western mountains (for the A2 scenario at mid-century).
- Precipitation is simulated by both the CMIP3 and NARCCAP models to generally increase in the north and decrease in the southwest. Under the A2 scenario, the changes are statistically significant in the far north and southwest by the end of the 21st century. In the central part of the country, these changes are either not statistically significant or the models are not in agreement on the sign of the changes. The range of model-simulated precipitation changes is considerably

larger than the multi-model mean change. Thus, there is great uncertainty associated with future precipitation changes in these scenarios.

- Changes in number of days with precipitation greater than 1 inch are not statistically significant over most of the country (for the A2 scenario at mid-century).
- The number of consecutive days with precipitation less than 0.1 inches shows statistically significant increases for the southwest. In most other areas, the changes are not statistically significant (for the A2 scenario at mid-century).
- Many models do not indicate a statistically significant change in temperature (with respect to 2001-2010) for the near future; however, as the time period progresses, a greater number of models simulate statistically significant temperature changes, with all being significant at the 95% confidence level by 2035 (for the high emissions scenario) and 2055 (for the low emissions scenario).
- Many of the modeled values of decadal precipitation change are not statistically significant, with respect to 2001-2010, out to 2091-2099.

A comparison of model simulations of the 20th century with observations indicates the following:

- The observed changes in temperature are generally within the envelope of modeled changes on an annual basis. For the summer season, the observed increase in temperature from the 1920s to the Dust Bowl era of the 1930s and the subsequent decrease from the 1930s to the 1940s are not simulated by any model. Most other seasonal changes are within the envelope of model simulations.
- The variability in observed precipitation change tends to be somewhat higher than that of the models, although decadal values are generally within the envelope of the model simulations.

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6.2. Future National Climate Scenarios

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A partial listing of reports appears below:

NESDIS 102 **NOAA Operational Sounding Products From Advanced-TOVS Polar Orbiting Environmental Satellites. Anthony L. Reale, August 2001.**

NESDIS 103 **GOES-11 Imager and Sounder Radiance and Product Validations for the GOES-11 Science Test. Jaime M. Daniels and Timothy J. Schmit, August 2001.**

NESDIS 104 **Summary of the NOAA/NESDIS Workshop on Development of a Coordinated Coral Reef Research and Monitoring Program. Jill E. Meyer and H. Lee Dantzler, August 2001.**

NESDIS 105 **Validation of SSM/I and AMSU Derived Tropical Rainfall Potential (TRaP) During the 2001 Atlantic Hurricane Season. Ralph Ferraro, Paul Pellegrino, Sheldon Kusselson, Michael Turk, and Stan Kidder, August 2002.**

NESDIS 106 **Calibration of the Advanced Microwave Sounding Unit-A Radiometers for NOAA-N and NOAA-N=. Tsan Mo, September 2002.**

NESDIS 107 **NOAA Operational Sounding Products for Advanced-TOVS: 2002. Anthony L. Reale, Michael W. Chalfant, Americo S. Allegrino, Franklin H. Tilley, Michael P. Ferguson, and Michael E. Pettey, December 2002.**

NESDIS 108 **Analytic Formulas for the Aliasing of Sea Level Sampled by a Single Exact-Repeat Altimetric Satellite or a Coordinated Constellation of Satellites. Chang-Kou Tai, November 2002.**

NESDIS 109 **Description of the System to Nowcast Salinity, Temperature and Sea nettle (*Chrysaora quinquecirrha*) Presence in Chesapeake Bay Using the Curvilinear Hydrodynamics in3-Dimensions (CH3D) Model. Zhen Li, Thomas F. Gross, and Christopher W. Brown, December 2002.**

NESDIS 110 **An Algorithm for Correction of Navigation Errors in AMSU-A Data. Seiichiro Kigawa and Michael P. Weinreb, December 2002.**

NESDIS 111 **An Algorithm for Correction of Lunar Contamination in AMSU-A Data. Seiichiro Kigawa and Tsan Mo, December 2002.**

NESDIS 112 **Sampling Errors of the Global Mean Sea Level Derived from Topex/Poseidon Altimetry. Chang-Kou Tai and Carl Wagner, December 2002.**

NESDIS 113 **Proceedings of the International GODAR Review Meeting: Abstracts. Sponsors: Intergovernmental Oceanographic Commission, U.S. National Oceanic and Atmospheric Administration, and the European Community, May 2003.**

NESDIS 114 **Satellite Rainfall Estimation Over South America: Evaluation of Two Major Events. Daniel A. Vila, Roderick A. Scofield, Robert J. Kuligowski, and J. Clay Davenport, May 2003.**

NESDIS 115 **Imager and Sounder Radiance and Product Validations for the GOES-12 Science Test. Donald W. Hillger, Timothy J. Schmit, and Jamie M. Daniels, September 2003.**

NESDIS 116 **Microwave Humidity Sounder Calibration Algorithm. Tsan Mo and Kenneth Jarva, October 2004.**

NESDIS 117 **Building Profile Plankton Databases for Climate and EcoSystem Research. Sydney Levitus, Satoshi Sato, Catherine Maillard, Nick Mikhailov, Pat Cadwell, Harry Dooley, June 2005.**

NESDIS 118 **Simultaneous Nadir Overpasses for NOAA-6 to NOAA-17 Satellites from 1980 and 2003 for the Intersatellite Calibration of Radiometers. Changyong Cao, Pubu Ciren, August 2005.**

NESDIS 119 **Calibration and Validation of NOAA 18 Instruments. Fuzhong Weng and Tsan Mo, December 2005.**

NESDIS 120 **The NOAA/NESDIS/ORA Windsat Calibration/Validation Collocation Database. Laurence Connor, February 2006.**

NESDIS 121 **Calibration of the Advanced Microwave Sounding Unit-A Radiometer for METOP-A. Tsan Mo, August 2006.**

NESDIS 122 JCSDA Community Radiative Transfer Model (CRTM). Yong Han, Paul van Delst, Quanhua Liu, Fuzhong Weng, Banghua Yan, Russ Treadon, and John Derber, December 2005.

NESDIS 123 Comparing Two Sets of Noisy Measurements. Lawrence E. Flynn, April 2007.

NESDIS 124 Calibration of the Advanced Microwave Sounding Unit-A for NOAA-N'. Tsan Mo, September 2007.

NESDIS 125 The GOES-13 Science Test: Imager and Sounder Radiance and Product Validations. Donald W. Hillger, Timothy J. Schmit, September 2007.

NESDIS 126 A QA/QC Manual of the Cooperative Summary of the Day Processing System. William E. Angel, January 2008.

NESDIS 127 The Easter Freeze of April 2007: A Climatological Perspective and Assessment of Impacts and Services. Ray Wolf, Jay Lawrimore, April 2008.

NESDIS 128 Influence of the ozone and water vapor on the GOES Aerosol and Smoke Product (GASP) retrieval. Hai Zhang, Raymond Hoff, Kevin McCann, Pubu Ciren, Shobha Kondragunta, and Ana Prados, May 2008.

NESDIS 129 Calibration and Validation of NOAA-19 Instruments. Tsan Mo and Fuzhong Weng, editors, July 2009.

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