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Severe Weather in United States Under a Changing Climate

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The science has become clear and convincing that the Earth's climate is rapidly changing [e.g., *Intergovernmental Panel on Climate Change* (*IPCC*), 2014]. Along with the overall changes in climate, there is strong evidence of an increasing trend over recent decades in the frequency, intensity, and duration of some types of extreme weather events, with resulting effects on U.S. society.

Since 1980, the United States has sustained 151 weather/climate disasters in which overall damages/costs reached or exceeded $1 billion (taking into account the Consumer Price Index adjustment to 2013 dollars), with an overall increasing trend (http://www.ncdc.noaa.gov/billions/). The total cost of these 151 events exceeds $1 trillion. In 2011 and 2012, there were more such weather events than in previous years, with 14 events in 2011 and 11 in 2012. Total costs in 2011 exceeded $60 billion, and total costs in 2012 exceeded $110 billion. The events include major heat waves, severe storms, tornadoes, droughts, floods, hurricanes, and wildfires. Even if hurricanes and their large, mostly coastal effects were excluded, there still would be an overall increase in the number of billion-dollar events over the past 30-plus years.

Recently, a series of related studies by *Kunkel et al.* [2013], *Peterson et al.* [2013], *Vose et al.* [2014], and *Wuebbles et al.* [2014] has led to a collective assessment regarding changes in various weather extremes relative to the changing climate. This assessment examined the adequacy of the existing data to detect trends in severe weather events relative to the current scientific ability to understand what drives those trends, i.e., how well the physical processes are understood and thus how the extremes are expected to change in the future.

This assessment shows that scientists have a strong understanding of the trends and underlying causes of the changes for some types of events, such as those relating to temperature and precipitation extremes. Adequate data for floods, droughts, and extratropical cyclones exist to enable researchers to detect trends in these events, but the underlying causes of their long-term changes are less well understood. Scientists also have only medium understanding of the trends and causes of changes in hurricanes and in snow events. For some events, such as strong winds, hail, ice storms, and tornadoes, there is insufficient understanding of the trends or of the causes for the trends to make strong conclusions currently about these events in a changing climate. These findings also correlate well with global analyses of climate extremes [*IPCC*, 2012].

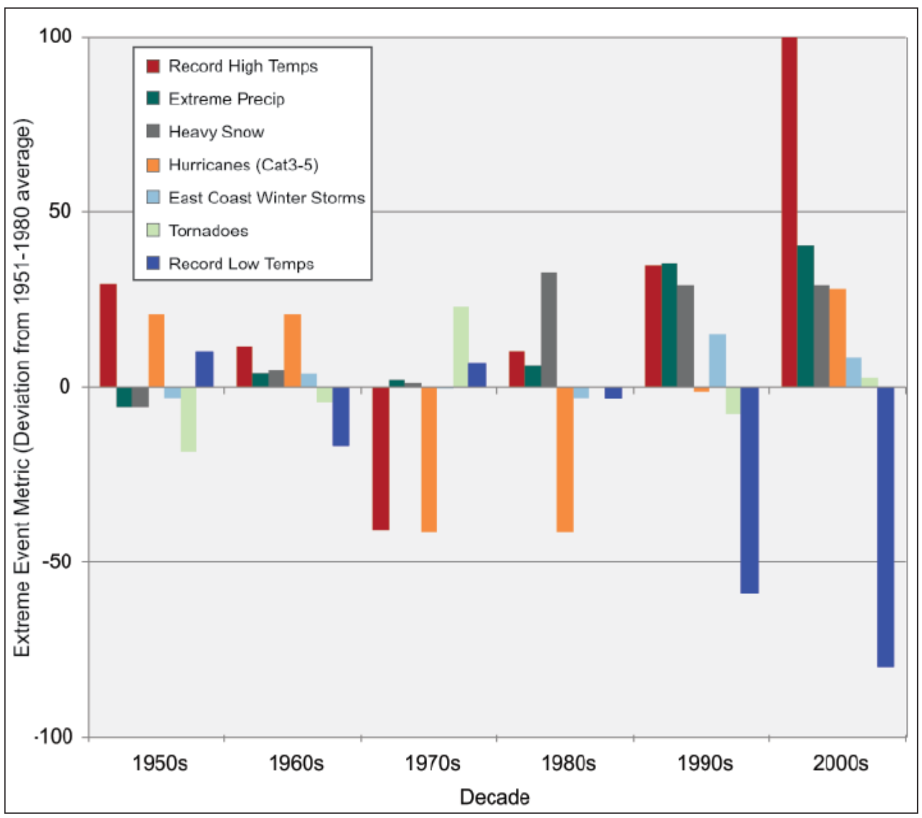

*Fig. 1. Extreme weather metrics for recent decades, including the number of record high monthly temperatures (red) [*Karl et al., *2012]; the number of daily precipitation events exceeding the threshold for a 1-in-20-year recurrence (dark green); the sum of the number of top 50 snowstorms for the U.S. regions east of the Rocky Mountains (gray; expansion of analysis in* Kunkel et al. *[2013]); the number of category 3, 4, or 5 hurricanes in the North Atlantic (orange; http://weather.unisys.com/hurricane/atlantic/); the number of strong East Coast winter storms (light blue; http://ecws.eas.cornell.edu/ECWS_graphs.html); the number of tornadoes of EF1 intensity or higher (light green; http://www.spc.noaa.gov/wcm/annualtornadomaps/); and the number of record low monthly temperatures (dark blue). The decade of the 2000s is the 12-year period of 2001–2012. Extreme precipitation events were determined from 3430 stations in the United States. Global Historical Climatology Network (GHCN) data set with less than 10% missing data for the period 1951–2011 following the methods of* Kunkel et al. *[2013].*

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Figures 1 and 2 provide examples of key findings (also see the workshop papers referenced above and the assessments and the references therein) demonstrating the current state of knowledge of extreme weather events affecting the United States in relationship to the changing climate. Figure 1 summarizes observed decadal changes in some extreme weather metrics for the past 6 decades. Figure 2 shows the projected changes in several types of extreme events for 2070–2099 relative to 1970–1999 over eight regions of the United States.

These analyses are based on climate model projections from the climate models participating in the fifth phase of the Coupled Model Intercomparison Project (CMIP5), focusing on the simulations of the 20th century based on natural and anthropogenic climate forcings and simulations of the 21st century based on the high-emissions scenario (RCP8.5) from the four new representative concentration pathways scenarios (RCPs). The RCP8.5 scenario assumes heavy continued use of fossil fuels through the end of the 21st century.

Extreme U.S. Temperature

Since 1895, U.S. annually averaged temperature has increased by 1.5°F. Most of the increases have taken place since 1970, culminating with the warmest year on record in the United States in 2012. Since 1991, temperatures have averaged 1°F to 1.5°F above the 1901–1960 average in most U.S. regions and 0.5°F in the Southeast.

The largest spatial extent of record breaking and much above normal mean monthly maximum and minimum temperatures has occurred in the first part of the 21st century. Figure 1 illustrates this, indicating a significant increase in record high temperatures in the past 2 decades and a significant decrease in record low temperatures. The recent heat waves and droughts in Texas (2011) and the Midwest (2012) set records for highest monthly average temperatures. While an event like the 2011 Texas heat wave and drought can be triggered by a naturally occurring event such as a deficit in precipitation, the chances for record-breaking temperature extremes have increased as the global climate has warmed. Heat waves, short-duration periods of extreme hot weather, have generally become more frequent across the United States in recent decades, with western regions (including Alaska) setting records for numbers of these events in the 2000s [*Peterson et al.*, 2013].

Rising temperatures over the next few decades will be affected by both the past history of anthropogenic emissions, along with natural variability, and the further changes in human-related emissions. Temperature increases over the second half of this century will be primarily determined by the pathway in future emissions, e.g., the differences between higher, fossil fuel–intensive scenarios compared to scenarios with lesser emissions. All regions of the United States are likely to be warmer. For the high-emissions RCP8.5 scenario, Figure 2a shows that the both the lowest minimum temperatures and the highest maximum temperature are projected to increase by very large magnitudes in all regions by the end of this century.

Extreme U.S. Precipitation

Since 1991, average annual precipitation has increased most in the Northeast, Midwest, and southern Great Plains regions, while much of the Southeast and Southwest has experienced a mix of increases and decreases. Projections suggest that this tendency will continue. The biggest effect on the United States could actually be the intensifying and expanding subtropical highs [*Li et al.*, 2013] and resulting reductions in winter and springtime precipitation in the Southwest.

Over the past couple of decades, the heaviest rainfall events have become more frequent (Figure 1), and the amount of rain falling in very heavy precipitation events has been significantly above average. This increase has been greatest in the Northeast, Midwest, and upper Great Plains.

Projected changes in annual mean precipitation are regionally variable (Figure 2b). In general, differences between wet and dry areas will increase across North America. However, for the RCP8.5 emissions scenario, extreme precipitation events are likely to increase by the end of this century in all regions (Figure 2b) while, with the exception of Alaska, all regions are likely to have more

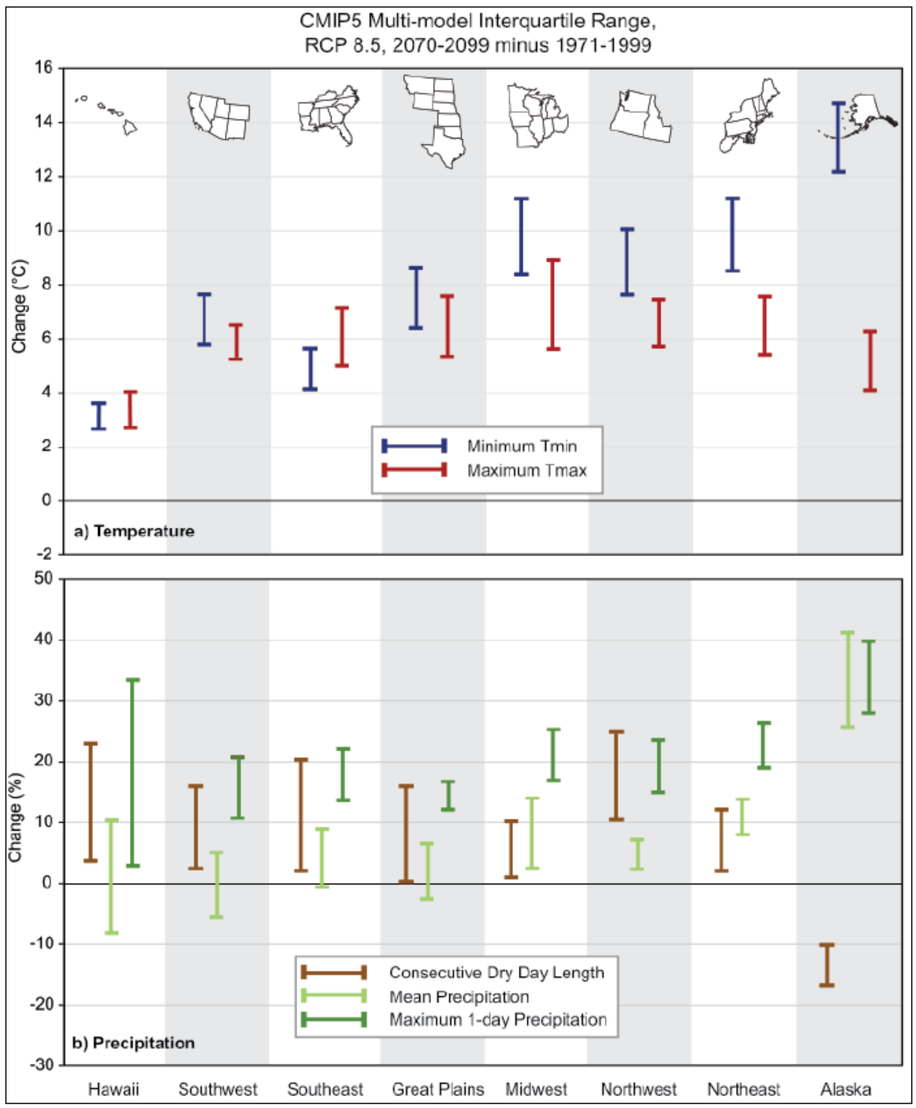

Fig. 2. Projected end of 21st century changes in the period averages of (a) annual maximum values of daily maximum temperature (TX_x) and annual minimum values of daily minimum temperature (TN_n) and (b) annual mean precipitation (P_{mean}), annual maximum 1-day precipitation (Rx1day), and annual maximum number of consecutive dry (<1 millimeter) days (CDD). This is based on 25 Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models (GCMs). The variables TX_x, TN_n, Rx1day, and CDD were obtained from the CLIMDEX (http://www.climdex.org/) archive.

consecutive days without precipitation, leading to longer dry seasons.

The total number of extreme snowstorms (based on the top 50 snowstorms in each region) has been substantially higher in the past 3 decades (Figure 1), especially in the northern United States. Such trends may continue as cold season moisture levels are likely to rise as long as temperatures remain cool enough in the northern regions for precipitation to fall as snow in winter storms.

Floods and Droughts

Despite a lack of nationwide trends in floods and droughts over the past century, there are definitive regional trends across the United States. Tree ring data suggest that the drought over the past decade in the western United States represents the driest conditions in 800 years, and prolonged periods of record high temperatures associated with droughts have contributed to conditions driving intense wildfires.

In general, warmer temperatures will increase evaporation and cause lower soil moisture even over some areas that will see increased precipitation. The drier soil is then a positive feedback for warmer and drier conditions in these areas and thus causes more frequent droughts. Under the RCP8.5 emissions scenario, drier soils are projected for the coming decades throughout the Southwest, stretching northeastward all the way to the Eastern Seaboard by the end of this century.

Floods also show regional trends. River flood magnitudes have decreased in the Southwest and increased in the eastern Great Plains, in parts of the Midwest, and from the northern Appalachians into New England. These regional river flood trends are qualitatively consistent with trends in climate conditions associated with flooding. For example, average annual precipitation has increased in the Midwest and Northeast and decreased in the Southwest. Flooding in the United States over the coming decades will continue to be regionally dependent. The areas most susceptible to increased seasonal flooding are likely to be across the north central and northeastern United States.

Changes in Hurricanes and Severe Storms

Since the early 1980s when the quality of the data improved, in part because of better coverage from satellites, there has been an increase in the intensity, frequency, and duration as well as the number of strongest (category 4 and 5) hurricanes documented in the Atlantic (Figure 1). The number of category 3, 4, and 5 North Atlantic hurricanes during the first decade of the 21st century was the highest since 1951. The recent increases in activity are linked, in part, to higher sea surface temperatures in the region where Atlantic hurricanes form and move through. Numerous factors have been shown to influence these local sea surface temperatures, including natural variability, human-induced emissions of heat-trapping gases, and particulate pollution, but the relative contributions remain an active focus of research.

By late this century, an increase in the strength and number of intense hurricanes is projected. These projected changes are based on an average of projections from a number of individual high-resolution models and mechanistic considerations [*Yamada et al.,* 2010; *U.S. CLIVAR Hurricane Working Group,* 2013; *Knutson et al.,* 2013]. Almost all existing studies project greater rainfall rates in hurricanes in a warmer climate, with projected increases of about 20% averaged near the center of hurricanes. Like hurricanes, the trends of severe storms have significant uncertainty in a warmer climate. The numbers of strong tornadoes and East Coast winter storms have not exhibited changes over the past 6 decades (Figure 1).

Confidence in Projections

In summary, the occurrence of certain types of severe weather is changing, and our ability to attribute the causes of these changes varies from very well to not at all depending on the type. For those types of events where our understanding of observed trends is strong, our confidence in projections of future changes is also high.

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