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TECHNICAL PAPER

Changes in weather and climate extremes: State of knowledge relevant to air and water quality in the United States

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Air and water quality are impacted by extreme weather and climate events on time scales ranging from minutes to many months. This review paper discusses the state of knowledge of how and why extreme events are changing and are projected to change in the future. These events include heat waves, cold waves, floods, droughts, hurricanes, strong extratropical cyclones such as nor'easters, heavy rain, and major snowfalls. Some of these events, such as heat waves, are projected to increase, while others, with cold waves being a good example, will decrease in intensity in our warming world. Each extreme's impact on air or water quality can be complex and can even vary over the course of the event.

Implications: Because extreme weather and climate events impact air and water quality, understanding how the various extremes are changing and are projected to change in the future has ramifications on air and water quality management.

Introduction

Weather and climate extremes with a billion dollars or more in insured and uninsured losses affect every state in the United States (Figure 1). Losses would be even greater if it were possible to assess losses related to human health and well-being, loss of life, and the ecological impacts of these events. The indirect costs of related poor air quality and hazards are also among the unaccounted for. In this article we focus on what we know about observed and projected changes in weather and climate extremes associated with natural catastrophes that also have the potential to compound their direct effects by affecting air and water quality.

The economic costs of extreme events are not homogeneous across the United States (see Figure 1). Both the climate and the exposure-related vulnerability to weather and climate extremes affect the spatial distribution of assessed economic impacts (IPCC, 2012). Not surprisingly, hurricane impacts are most frequent in the southeast, as are heat waves. Flooding events are widespread, but particularly noteworthy in states along major rivers. For the most part, wildfire is a western U.S. phenomenon, but billion-dollar droughts and heat waves do affect every state with the exception of Alaska and Hawaii. Ice storms, off-season freezes, and severe local weather affect many other portions of the United States, but have more limited influence on air and water quality so they are not addressed in this review. Compound and closely spaced extreme events can be very important, but there is much less research on the frequency and changes in frequency of closely spaced and concomitant extreme weather and climate events (Karl et al., 2009). In some instances, however, we do have valuable information about the frequency of concomitant occurrences. The Second National Climate Assessment of Global Climate Change Impacts in the United States (Karl et al., 2009) indicates that more than 25% of the heat waves in the south and western parts of the United States occur with stagnant air conditions. Similarly, a heat wave following a hurricane or a severe local storm with prolonged power interruption can lead to rapid escalation of a variety of human health issues. Also, the impacts of simultaneous drought, heat waves, and wildfires can lead to simultaneous insults to human health related to the cumulative effects of heat stress, poor air quality, and poor water quality and quantity.

Extreme events, by definition, can be both rare at any given location and common in a global sense. In any one place, the chance of a once in 100 years heat extreme is so rare that, in principle, it only occurs, on average, once every 100 years. This also means that, on average and with a non-changing climate, every year 1% of the United States would be expected to

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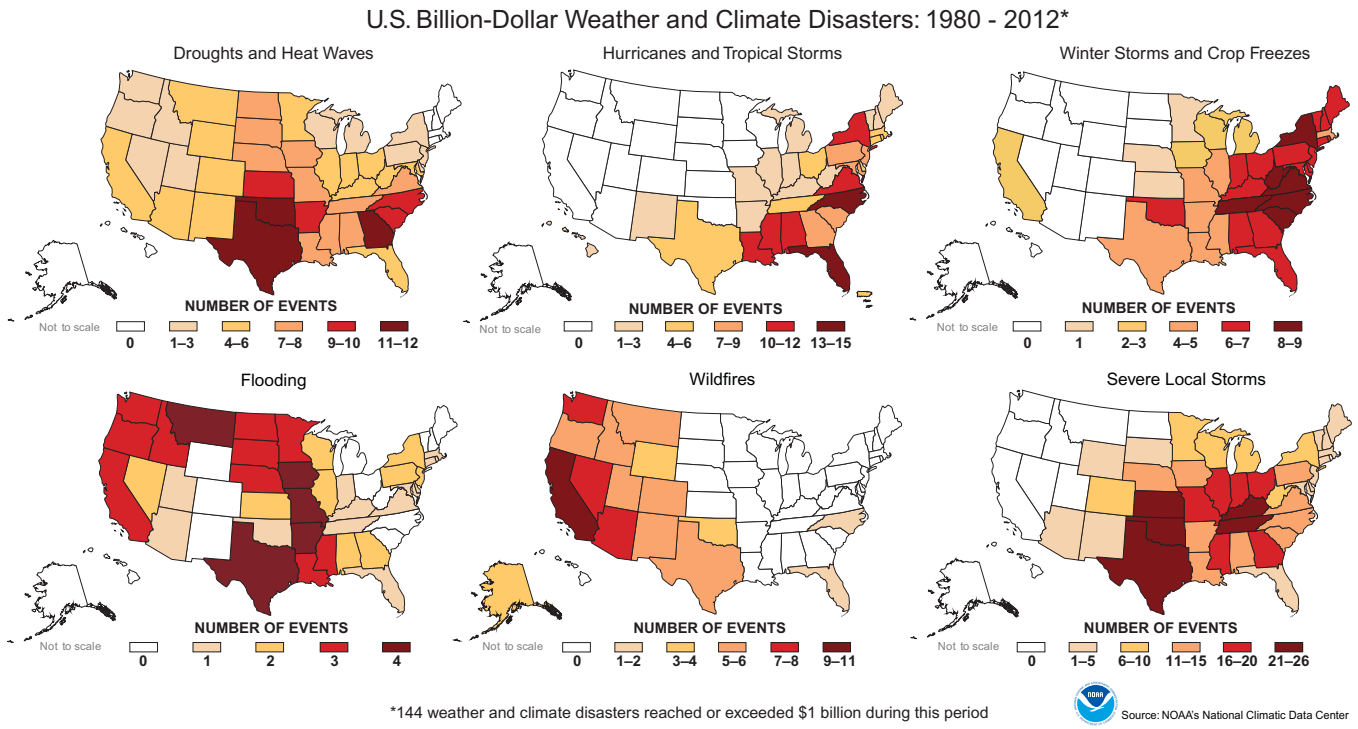

Figure 1. Number of billion-dollar events (including Consumer Price Index adjustment to 2011) by event category for the period 1980–2011, aggregated to state level. Costs of wide-area events are apportioned across states, and may not amount to $1B of damage in each affected state. The Severe Local Storms and Tornadoes map reflects billion-dollar events for combined tornado, hail, and straight-line wind damage. *Source*: NOAA/NCDC.

experience a once in 100 years heat extreme and 1% a cold extreme (Peterson et al., 2013a). But there are multiple definitions for what precisely is a heat wave or extreme heat event (Perkins and Alexander, 2013). The most extreme events can have the greatest impact. But the occurrence of these events is so rare that there are too few data points to determine robust trends. Therefore, climatologists often set the threshold for determining what is an extreme such that it would provide enough events to determine how extremes are changing (Peterson et al., 2008a).

Our ability to monitor multidecadal changes in a variety of extreme weather and climate events varies with the phenomena. Not surprisingly, the more confidence we have in our ability to detect changes, the more likely we are to better understand the causes of observed changes (Figure 2). For example, we have better confidence in our ability to detect and understand the causes of observed changes in the frequency and intensity of heat waves compared to tornadoes or thunderstorm generated extreme winds. Fortunately, our confidence is greatest for many of the phenomena that are most relevant to air and water quality management. However, while we can quantitatively describe how these extremes are changing, the current state of knowledge prevents us from providing robust quantitative information on the direct impact of these changes in extremes on air or water quality, leaving this part to be more qualitative in nature.

In this review article we assess observed trends and changes in context with future projections for many of the extreme events that are components of the Annual Extremes Index depicted in Figure 3. In addition, here we also consider severe snowstorms. As evident in Figure 3, over the last several decades there has been an increase in the frequency of extreme weather and climate events after a "quiet" period of 30 years in the middle of the 20th century when climate and weather extremes were less prevalent. This increasing trend in extremes is discussed in the context of projections of our warming planet.

Air Quality

Heat waves and drought

Air quality is defined by the level of pollution within the air, not the temperature of the air. Yet there are aspects of meteorological conditions related to the air's temperature that can impact air quality through concentrating, diluting or chemical processing pollution in the atmosphere (Fiore et al., 2012). Analysis of daily temperature observations taken at weather observing stations across the United States indicate that over the last several decades heat waves are generally increasing (Peterson et al., 2013b). With continuing rising high temperatures, extreme heat waves that are currently considered rare will occur more frequently in the future. Indeed, model studies indicate that intense heat waves that now occur once every 20 years are projected to occur about every other year in much of the country by the end of this century (Karl et al., 2009). While an increasing number of heat waves is in keeping with expectations in a warming climate, decadal variations in the number of U.S. heat and cold waves do not correlate that closely with the

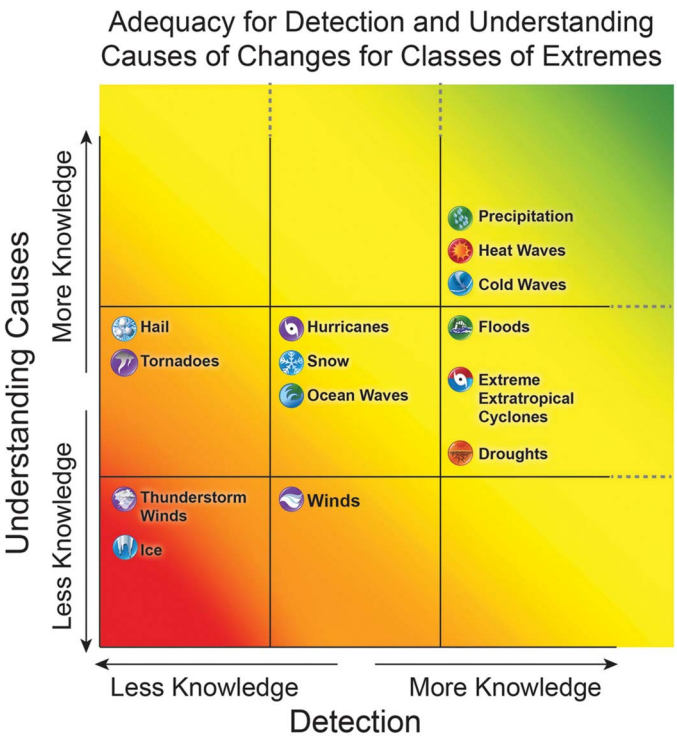

Figure 2. The collective assessment of the state of knowledge regarding changes in various extreme events (Kunkel et al. 2013a; Peterson et al. 2013b; Vose et al. 2013). The x-axis refers to the knowledge about our ability to correct for and quantify the time-dependent biases and spatial and temporal completeness of the data to detect multidecadal trends. The y-axis refers to scientific understanding of what drives those trends, that is, how well the physical processes are understood, and thus how much confidence we have in projecting changes in future extreme events. For each axis, the extreme phenomena are assigned to one of three categories of knowledge (from less to more). The dashed lines on the right side and top of the graph imply that the knowledge about the phenomena is not complete.

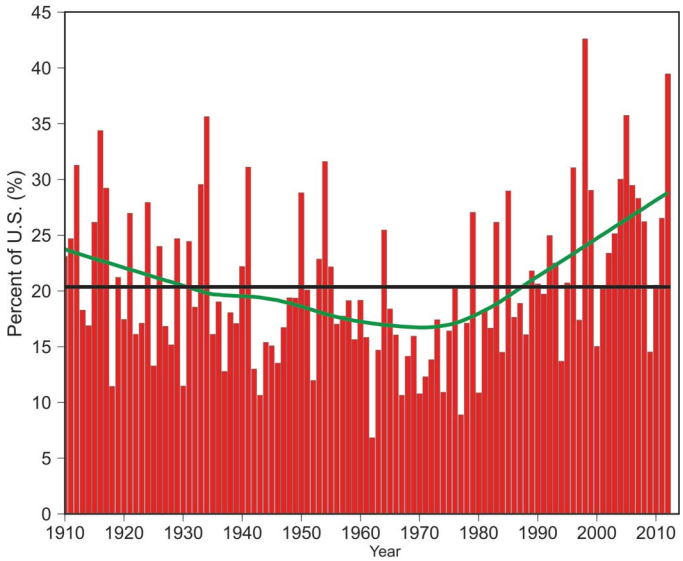

Figure 3. Annual U.S. Climate Extremes Index, 1910–2012. The index is scaled to reflect the percent of the contiguous United States affected by these extreme events during the course of the year. Vertical bars indicate the annual percentage of the continuous U.S. land area experiencing extreme conditions; straight (black) line is the average over entire period of record; smoothed (green) line shows a locally weighted linear regression method (lowess filter) to indicate multidecadal changes using a smoothing span equal to 50% of the time series length. The index considers extremes in monthly mean maximum and minimum temperature, soil moisture excess and deficits, extremes in 1-day precipitation, extremes in days with or without precipitation, and landfalling tropical storm and hurricane wind speed and duration. Several important extremes are not yet reflected in the index, including tornados and severe thunderstorm outbreaks, ice storms, and blizzards/snowstorms. More details about the Climate Extremes Index are provided in Gleason et al. (2008).

warming observed over the United States. For example, the drought years of the 1930s had the most heat waves (Peterson et al., 2013b), even though the decade of the 2000s was warmer. One of the reasons is that droughts and heat waves are closely related. For droughts, multiyear and longer variability dominate the climate signal.

Drought across the globe is primarily controlled by circulation patterns and their related ocean surface temperature patterns such as La Niña (Sheffield and Wood, 2011; Rupp et al., 2012). But locally, droughts are typically "linked to a persistent upper-level high pressure system or ridge that brings with it an inversion layer (layer of warm air aloft) and sinking air. Both of these are unfavorable for the formation of clouds and precipitation" (Mogil, 2007, pp. 185–186).

High pressure and ridge systems and their associated subsidence and inversion layers have been related to poor air quality in some regions (e.g., Lee et al., 2012a; Wang et al., 2012). This is in part because the air is stagnant, trapping emitted pollutants, but it is also partly due to the lack of precipitation. Precipitation processes can take up and remove soluble trace gases and aerosols, thereby cleaning the air (Neu and Prather, 2012). To make matters worse, it has long been noted that there are self-perpetuating features of a drought, such as drying of the soil, which provides less moisture for downwind precipitation, which can lead to droughts persisting and even expanding (National Science Board, 1972; Oliver and Fairbridge, 1987). Additionally, drought can alter plants' normal interactions with air pollution. For example, citrus trees take up ozone through stomatal mechanisms. But their leaves also emit biogenic volatile organic compounds that can remove ozone through gas-phase chemical reactions but oxidize to form ozone as well (Fares et al., 2010).

Furthermore, drought is often accompanied by hot conditions. Indeed, "some of the most extreme, prolonged, and high-impact heat waves in the U.S. are bolstered by positive, reinforcing feedbacks related to low-humidity and drought conditions" (Peterson et al., 2013b, p. 825). The physics involves both fewer clouds to reflect sunlight during a drought and less surface moisture available for evaporation and evapotranspiration, which causes a higher percentage of the sunlight reaching the surface to be converted into sensible heat. Additionally, high temperatures have large impacts on some pollutants such as tropospheric ozone. As a result, substantial increases in surface ozone have been documented during heat wave episodes (Hodenbrog et al., 2012).

Future projections of extreme hot days were investigated using regional climate model simulations from the North

American Regional Climate Change Assessment Program (NARCCAP; Mearns et al., 2009, 2012). NARCCAP modelers run a set of regional climate models that are driven by global atmosphere–ocean general circulation models over a domain covering the conterminous United States and most of Canada. Simulations were available for the future period of 2041–2070 and a control period of 1971–2000. The NARCCAP model projections of hot days show large increases over the entire contiguous United States by about the middle of the 21st century under a high emissions scenario (Figure 4) with respect to the late 20th century. The number of days above 90°F (32.2°C) increases by 25–50 in much of the southern United States, with increases of 10–25 days in much of the North. The number of days above 100°F (37.8°C) increases by 15–30 days in much of the South and 5–15 days in the center and North. Only in far northern and high elevation areas do 100°F (37.8°C) days remain rare.

Ozone concentrations are strongly dependent on temperature (Weaver et al., 2009). The large increases in very hot days will increase O_3 concentrations if other factors do not change. Indeed, air quality model simulations have generally shown future increases in the number of exceedances of O_3 standards, due to the dominating influence of temperature increases, although in some model simulations there are regional decreases due to counteracting effects of solar insolation decreases (Weaver et al., 2009). Additionally, model simulations generally show that a shift in mean temperature is the dominant change in future heat wave occurrence, rather than a change in width of the probability density function (Kunkel et al., 2010).

Relationship of heat and drought to forest fires. An additional air pollution challenge during droughts is smoke from wildfires. As pointed out in the Second National Assessment (Karl et al., 2009), in the western United States, both the frequency of large wildfires and the length of the fire season have increased substantially in recent decades, due primarily to earlier spring snowmelt and higher spring and summer temperatures (Westerling et al., 2006). These changes in climate have reduced the availability of moisture, drying out the vegetation that provides the fuel for fires. Alaska also has experienced large increases in fire, with the area burned more than doubling in recent decades. As in the western United States, higher air temperature is a key factor. In Alaska, for example, June air temperatures alone explained approximately 38% of the increase in the area burned annually from 1950 to 2003 (Ryan et al., 2008).

The conditions Westerling et al. (2006) determined increased wildfires were found by Running (2006) to be entirely consistent with the conditions that models were projecting for the future. Running therefore concludes that increases in wildfires in the western United States seem likely. Complicating projections for future wildfires is the uncertainty surrounding future wildfire mitigation strategies (Burton, 2013; Ellenwood et al., 2012).

The most reliable historical wildfire data extends only back to 2001 (see Figure 5) and shows considerable year to year variability in the acres burned. Figure 6 shows that the majority of the acres are burned during the summer months. The smoke from wildfires is a serious medical hazard (e.g., Shusterman et al., 1993; Rappold et al., 2012). Additionally, it can reduce visibility on a local scale (Peterson et al., 2008b). Even on regional scales the negative impact on visibility is clearly apparent (Park et al., 2006), including within urban environments (Wise, 2008).

Cold waves and snow

Generally speaking, there are two types of cold waves (Peterson et al., 2013b). One is when a deep-layer, dry, stable, cold air mass comes barreling down from Alaska or Northern Canada accompanied by high winds and low wind chills. The second is a shallow layer of dry, cold and stable air with calm

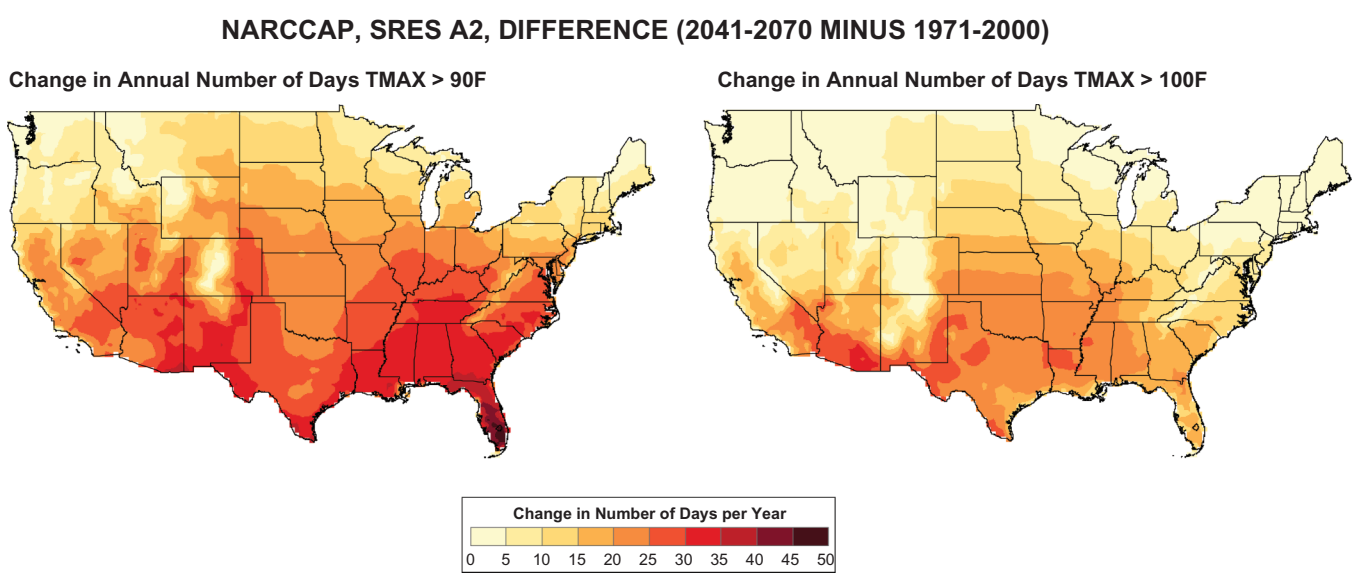

Figure 4. Simulated difference in the mean annual number of days with a maximum temperature greater than 90°F (32.2°C) (left) and 100°F (37.8°C) (right) for the contiguous United States, for the 2041–2070 time period with respect to the reference period of 1971–2000 for a high (SRES A2) emissions scenario. These fields are multimodel means for nine regional climate simulations from the North American Regional Climate Change Assessment Program (NARCCAP).

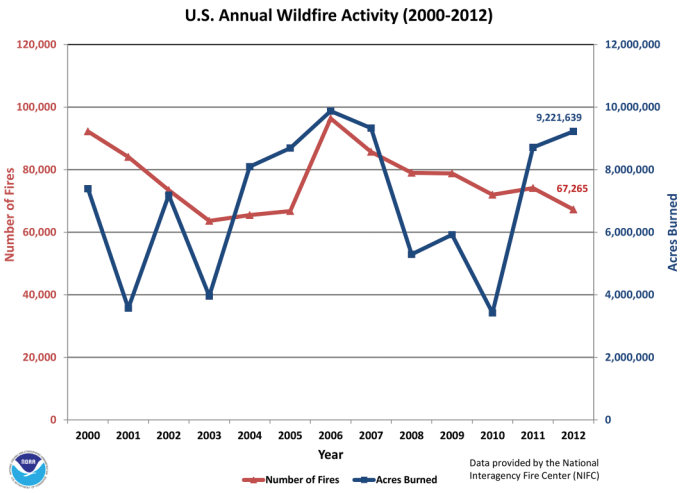

Figure 5. U.S. annual wildfire activity expressed both in terms of the number of fires (red triangles) and the acres burned (blue squares). Data from The National Interagency Fire Center (NIFC).

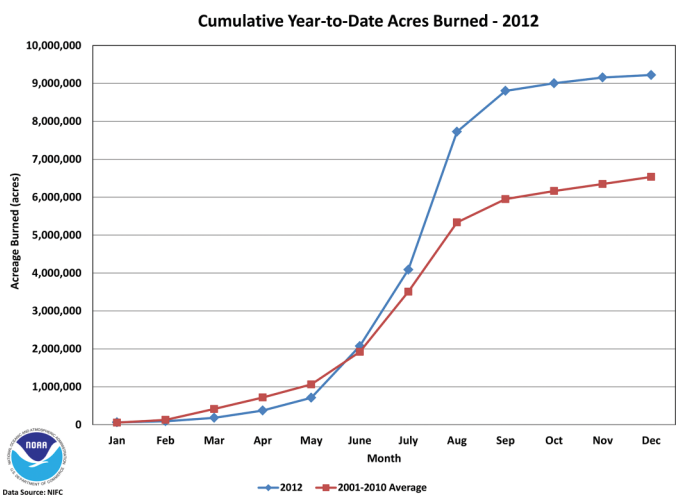

Figure 6. Cumulative acres burned in 2012 and the 2001–2010 average. Note that the steep rise in acres burned is during the summer months. Data from the National Interagency Fire Center (NIFC).

winds that can persist over snow-covered areas. The second type of cold wave can last longer than the first but has a smaller spatial extent. The first is strengthened by large-scale atmospheric circulation patterns favoring cold air advection, while the second is reinforced by clear-sky radiative cooling. Therefore, the impact of a cold wave on air quality depends on the type of cold wave it is. The first type tends to advect in well-mixed upwind air conditions (e.g., Lee et al., 2012b), while the second type allows local air pollution to accumulate (e.g., Lareau et al., 2013).

Inversions, with cold air near the surface and warmer air aloft, can trap pollutants. Persistent inversions occur most frequently in areas of the United States where the topography is conducive to the pooling of cold and stable air in valleys (Gilles et al., 2010). This can be particularly true in northern locations like Fairbanks, AK, where the short midwinter day length means that peak traffic hours in the morning can occur when the ground-based nighttime inversion layer is still in place. With mixing heights as low as 10 m and light winds, air pollution such as carbon monoxide can be a serious problem (Bowling, 1986). Though the climate is warming, like short day lengths, nighttime inversion layers will still continue in areas that favor them—though the temperature at the surface will likely be warmer.

In recent decades, the number of cold waves in the United States has been decreasing (Peterson et al., 2013b). While this is in keeping with expectations in a warming climate, it turns out that decadal variations in the number of U.S. cold waves do not correlate well with the observed U.S. warming during the last century. Since 1900, the decade with the highest number of cold waves was the 1980s and the lowest the 2000s (Peterson et al., 2013b). The cold air mass main source regions of arctic and subarctic Canada are warming on multidecadal time scales (Hankes and Walsh, 2011). Strong warming of the coldest nights experienced over much of the United States since 1950 is consistent with this warming of the North American cold air mass source regions.

In contrast to extreme hot days, NARCCAP model projections of cold days (Figure 7) show large decreases by the about the middle of the 21st century with respect to the late 20th century. The number of days below 0°F (–17.8°C) (Figure 7 left) decreases by 5–20 days in much of the North and they become rare or do not occur at all in the South in the future. The number of days below freezing (Figure 7 right) decreases by 15–25 days in much of the east and 25–40 days in much of the west.

Trends in snowfall. Snow cover promotes development of inversions through the reflection of solar radiation and persistence of cold temperatures near the surface, while a lack of snow cover leads to greater diurnal heating, which erodes inversions (Maleck et al., 2006; Bailey et al., 2011). The former conditions often occur following major winter storms when heavy snowfall is followed by clearing skies and strengthening high pressure. Changing patterns of snowfall that occur in association with warming winter temperatures can therefore affect the frequency and intensity of surface inversions. Declining trends in snowpack in the western U.S. and a reduction in snow cover extent in the U.S. have occurred since the middle of the 20th century, along with a decrease in total snowfall and in the ratio of snowfall to total precipitation. A decrease in the November–March ratio of snowfall to total precipitation has occurred most notably in the western and central U.S. where winter warming has been the greatest (Feng and Hu, 2007). These results are consistent with other research that has found a reduction in the amount of total snowfall in most areas of the country from 1930 through 2007 (Kunkel et al., 2009).

Perhaps surprisingly, while snowfall has decreased there is evidence of an increase in recent decades in the frequency of the most severe snowstorms (Kocin and Uccellini, 2004; Kunkel et al., 2013a). A Regional Snowfall Index that was developed to quantify the severity of snowstorms based on snowfall amount and coverage reveals a near doubling in the number of extreme

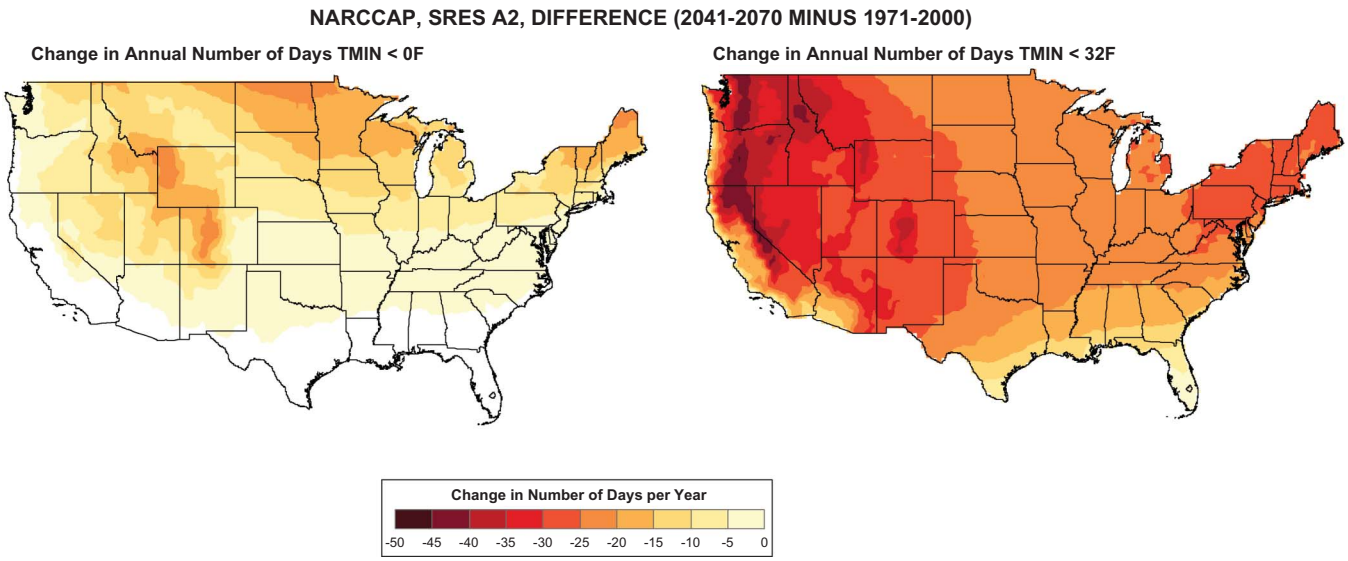

Figure 7. Simulated difference in the mean annual number of days with a minimum temperature less than 0°F (–17.8°C) (left) and 32°F (0°C) (right) for the contiguous United States, for the 2041–2070 time period with respect to the reference period of 1971–2000 for a high (SRES A2) emissions scenario. These fields are multimodel means for nine regional climate simulations from the North American Regional Climate Change Assessment Program (NARCCAP). The white area in the left panel indicates areas where the number of occurrences is near-zero in both present and future periods of the simulations.

regional snowstorms in 1950 to 1999 compared to the 1900 to 1949 period (Figure 8; Kunkel et al., 2013a).

While a decrease in snow cover extent and seasonal snowfall totals may on a seasonal basis decrease the frequency of conditions conducive to surface inversions, in areas where rare but severe snowstorms occur, the resulting heavy snowpack can create conditions conducive to persistent surface inversions. When power outages occur in association with these storms, air quality problems may be exacerbated by the use of wood- and coal-burning stoves, fireplaces, and gas or diesel generators that emit higher levels of particulates (Bond et al., 2004).

Water Quality

Floods

Overview of causes of extreme precipitation. As noted by Kunkel et al. (2012), there are various causes of extreme precipitation (and thus flooding) in the conterminous United States. Very generally, during the cold season widespread heavy precipitation is typically associated with extratropical cyclones, their concomitant warm and cold fronts, and the mesoscale convective complexes initiated along frontal boundaries. During the warm season extreme precipitation is often attributed to tropical cyclones, the North American monsoon, and isolated thunderstorms occurring in unstable air masses. Impervious surface cover can exacerbate the impact of heavy precipitation, increasing the magnitude and extent of flooding. For example, paved surfaces can accelerate runoff rates in the urban environment, and rapid snow melt, particularly when coincident with intense rainfall, can enhance river flooding.

There is some evidence that air pollution can increase convective storms. The groundbreaking METROMEX (METROpolitan Meteorological EXperiment) of the 1970s found that precipitation and convective storms were enhanced downwind (east and northeast) of St. Louis, MO. The observed summer increases were up to 30% more rainfall and 45% more thunderstorm days, compared to the regional averages (Changnon et al., 1976; Changnon, 1978). One of the hypothesized causes was enhanced aerosol concentrations (Changnon et al., 1976). Bell et al. (2008) found that the average storm

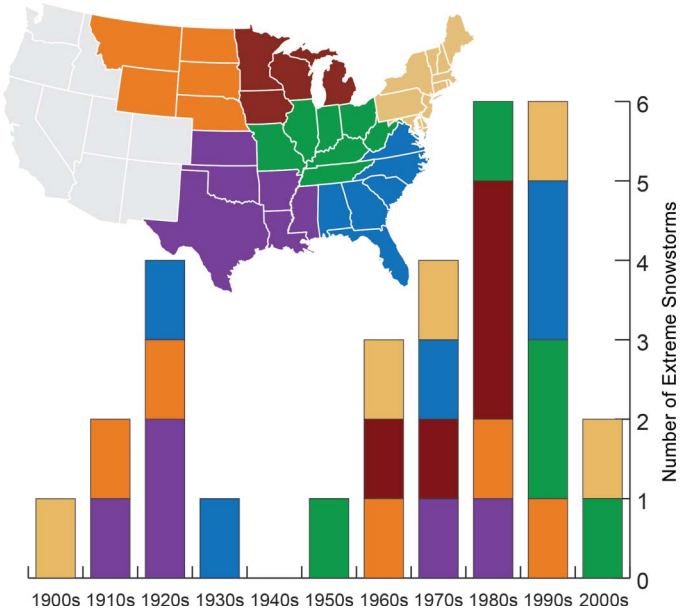

Figure 8. Number of extreme snowstorms (upper 10th percentile) occurring each decade within the six U.S. climate regions in the eastern two-thirds of the contiguous U.S. (based on an analysis of the 50 strongest storms for each of the six climate regions from October 1900 through April 2010). The inset map shows the boundaries of each climate region. These regions were selected from Kunkel et al. (2013a).

rainfall in the afternoon was higher in mid-week (when pollution levels were higher) than on the weekend in the southeastern U.S. Rosenfeld and Bell (2011) also found that tornadoes and hailstorms occur in higher numbers during mid-week in the eastern U.S. A possible mechanism for such effects derives from aerosols' role as nuclei for cloud droplet condensation. A polluted air mass can be high in condensation nuclei. When such air is drawn into incipient convective clouds, it can initially delay the formation by coalescence of water drops large enough to fall as rain, because the cloud is composed of a large number of very small droplets that compete for the finite supply of water vapor. This results in a greater fraction of the water mass being lifted vertically into the higher and colder freezing layer where the additional latent heating of fusion invigorates the convective storms and results in an overall increase in rainfall (Bell et al., 2008). Similarly, when a tropical cyclone encroaches on land in a region of high pollution aerosol concentration, the convection and latent heat release in the storm periphery can lead to locally increased rainfall as the aerosols are drawn into the storm's outer rainbands. But this increase may also compete with and weaken the convection near the storm center, ultimately weakening the most intense winds (see the appendix on tropical cyclones for further detail).

There have been numerous studies of trends in extreme precipitation events in the U.S. and these have found increases in heavy precipitation events when aggregated to the national level (e.g., Kunkel et al., 2013a; Groisman et al., 2012). There are substantial variations in the spatial distribution of statistically significant trends (e.g., Bonin et al., 2011). Various metrics of extremes have been utilized in these studies. Figure 9 shows an analysis of changes in the amount of precipitation falling on days that exceed the 99th percentile of daily precipitation amounts (this threshold is computed from the set of days with measurable precipitation). The figure shows the change in the amount of heavy precipitation for the most recent 30-year period, 1983–2012, with respect to the previous 30-year period, 1953–1982, for seven regions. In each of the regions, the amount of heavy precipitation in the most recent 30-year period is greater than in the previous 30 years, although the change in the northwest and southeast are very small. The largest changes of greater than +20% are in the Midwest and Northeast.

Model simulations of future changes suggest a high likelihood that this trend will continue. Changes of 20–30% in the magnitude of the most extreme events are projected under a high emissions scenario (Kunkel et al., 2013b). There is high confidence in this projection because increases in air temperature under such a scenario will lead to the potential of high water vapor content in the atmosphere and more available moisture for extreme precipitation-producing weather systems. Numerical projections of tropical cyclone-related rainfall rates are more robust and consistent than projections of tropical cyclone frequency, track, or intensity, and there is, to use Mastrandea et al. (2010) terminology, medium confidence that rainfall rates near the centers of tropical cyclones will increase in a warming world (Knutson et al., 2010; Ying et al., 2012). The increase in rainfall rates associated with tropical cyclones is a consistent feature of the numerical models under greenhouse warming as atmospheric moisture content in the tropics and tropical cyclone moisture convergence is projected to increase (Allan and Soden, 2008; Knutson et al., 2010; Knutson et al., 2013; Trenberth et al., 2007; Trenberth et al., 2005). Although no detectable long-term changes in tropical cyclone rainfall rates have yet been reported, Santer et al. (2007) detected an increase in atmospheric moisture content over ocean regions where tropical cyclones track, and attributed the moisture increase to anthropogenic surface warming.

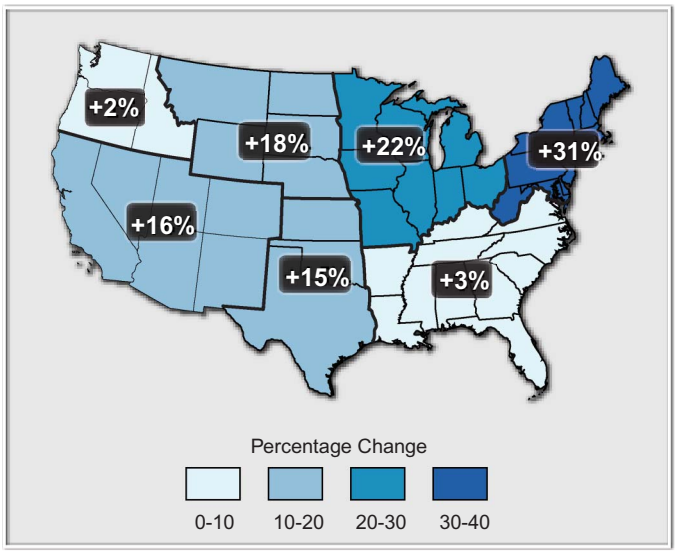

Figure 9. The total amount of precipitation falling on days that exceed the 99th percentile threshold of daily precipitation amounts during the 30-year period of 1983–2012 with respect to the prior 30-year period of 1953–1982. The differences are expressed as percent of the 1953–1982 values.

Impacts on urban wastewater. The U.S. Environmental Protection Agency (EPA) (2013) states that

> Combined sewer systems are sewers that are designed to collect rainwater runoff, domestic sewage, and industrial wastewater in the same pipe. Most of the time, combined sewer systems transport all of their wastewater to a sewage treatment plant, where it is treated and then discharged to a water body. During periods of heavy rainfall or snowmelt, however, the wastewater volume in a combined sewer system can exceed the capacity of the sewer system or treatment plant. For this reason, combined sewer systems are designed to overflow occasionally and discharge excess wastewater directly to nearby streams, rivers, or other water bodies. These overflows, called combined sewer overflows (CSOs), contain not only stormwater but also untreated human and industrial waste, toxic materials, and debris. They are a major water pollution concern for the approximately 772 cities in the U.S. that have combined sewer systems

which are mainly in older northern cities from Maine to Iowa and in the Pacific Northwest (EPA, 2013). Therefore, increases in

heavy precipitation events over these urban areas would present special water quality challenges.

River flooding. Annual peak river and stream flow data reveal that river flooding trends on a century scale do not show uniform changes across the country. While flood magnitudes in the Southwest have been decreasing, flood magnitudes in the Northeast and in the north central United States have been increasing (Figure 10). Because changes in river flooding can be caused by changes in atmospheric conditions (e.g., precipitation amount, type, and timing, as well as temperature), land use/land cover (e.g., agricultural practices, urbanization), and water management (e.g., dams, diversions, and levees), the stream gauge stations shown in Figure 10 are part of a carefully selected subset of U.S. stream gauges that that have experienced little or no land-use or water-management changes. Further confounding the analysis of trends in river flooding is multiyear and even multidecadal variability likely caused by both large-scale atmospheric circulation changes and basin-scale "memory" in the form of soil moisture.

When it comes to long-term, century-scale changes in river flooding, we find that the results shown in Figure 10 have considerable regional similarity to maps of century-scale changes in total precipitation (Peterson et al., 2013b). When we look toward the end of the century, projections of future precipitation generally indicate that northern areas will become wetter, and southern areas, particularly in the West, will become drier (Karl et al., 2009).

The effect of flooding on water quality is complex. High water can dilute some pollutants but also entrain others, such as nitrogen leaching from flooded farmland (BryantMason et al., 2013; Wiegner et al., 2013). But even within the same river basin, differences in the source regions of the flood water can result in very different levels of dissolved nitrogen, phosphorus, and suspended solids (Morris, 2012). Flooding of industrial areas or agricultural chemical storage locations can mobilize chemicals and not only lead to degradations of water quality but also contaminate flooded residential areas (Euripidou and Murray, 2004). In addition to water flowing into and overwhelming wastewater treatment plants discussed earlier, flooding can inundate low-lying wastewater treatment plants.

Coastal storm surge and inland flooding. Strong extratropical cyclones can result in heavy precipitation, widespread icing, and high winds over large portions of the United States. Coastal regions are particularly vulnerable as onshore flow exacerbates tides and increases storm surge, pummeling costly near shore infrastructure. At present there is suggestive evidence of an increase in storm activity around U.S. coastlines during the second half of the 20th century (Vose et al., 2013). There is also suggestive evidence of an increase in extreme winds along the coasts in recent decades (Pryor et al., 2009; Young et al., 2011), as well as an increase in extreme waves along the Pacific coast (Bromirski et al., 2003; Dee et al., 2011; Gulev and Grigorieva, 2004), consistent with an increase in extratropical cyclone activity. Current model projections do not lead to conclusive answers regarding extratropical cyclone trends in the future (Bengtsson et al., 2009), but long-term increases in sea level will likely spread the impacts farther inland even if extratropical cyclone activity remains roughly the same as present-day activity.

A significant upward trend in the frequency of large sea-level anomaly events along the U.S. East Coast and Gulf Coast has been identified in an 86-year tide-gauge record, and this trend has been argued to represent a trend in storm surge associated with landfalling hurricanes (Grinsted et al., 2013). Similarly, Bromirski and Kossin (2008) identified significant upward trends in wave power in the Atlantic Ocean and Gulf of Mexico. If these trends continue and combine with the compounding factor of projected sea-level rise, coastal impacts from storm surge are likely to increase substantially.

While storm surge results mainly in coastal saltwater flooding, freshwater flooding associated with tropical cyclones can occur well inland from the coast, and projected increases in

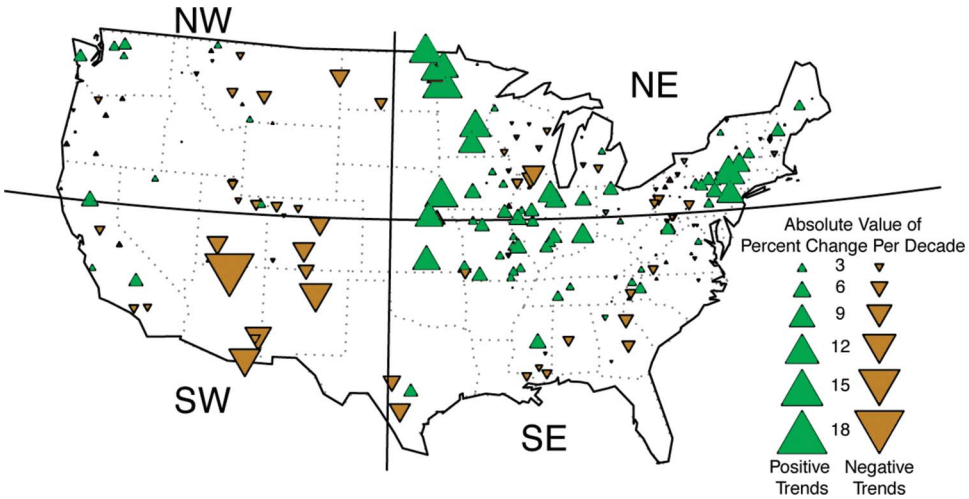

Figure 10. Geographic distribution of century-scale changes in flooding. The triangles are located at 200 streamgages which have record lengths of 85–127 years. The selection of these sites is described by Hirsch and Ryberg (2012). The color and size of the triangles are determined by the trend slope of a regression of the logarithm of the annual flood magnitude versus time for the entire period of record at the site, ending with water year 2008. From Peterson et al. (2013b).

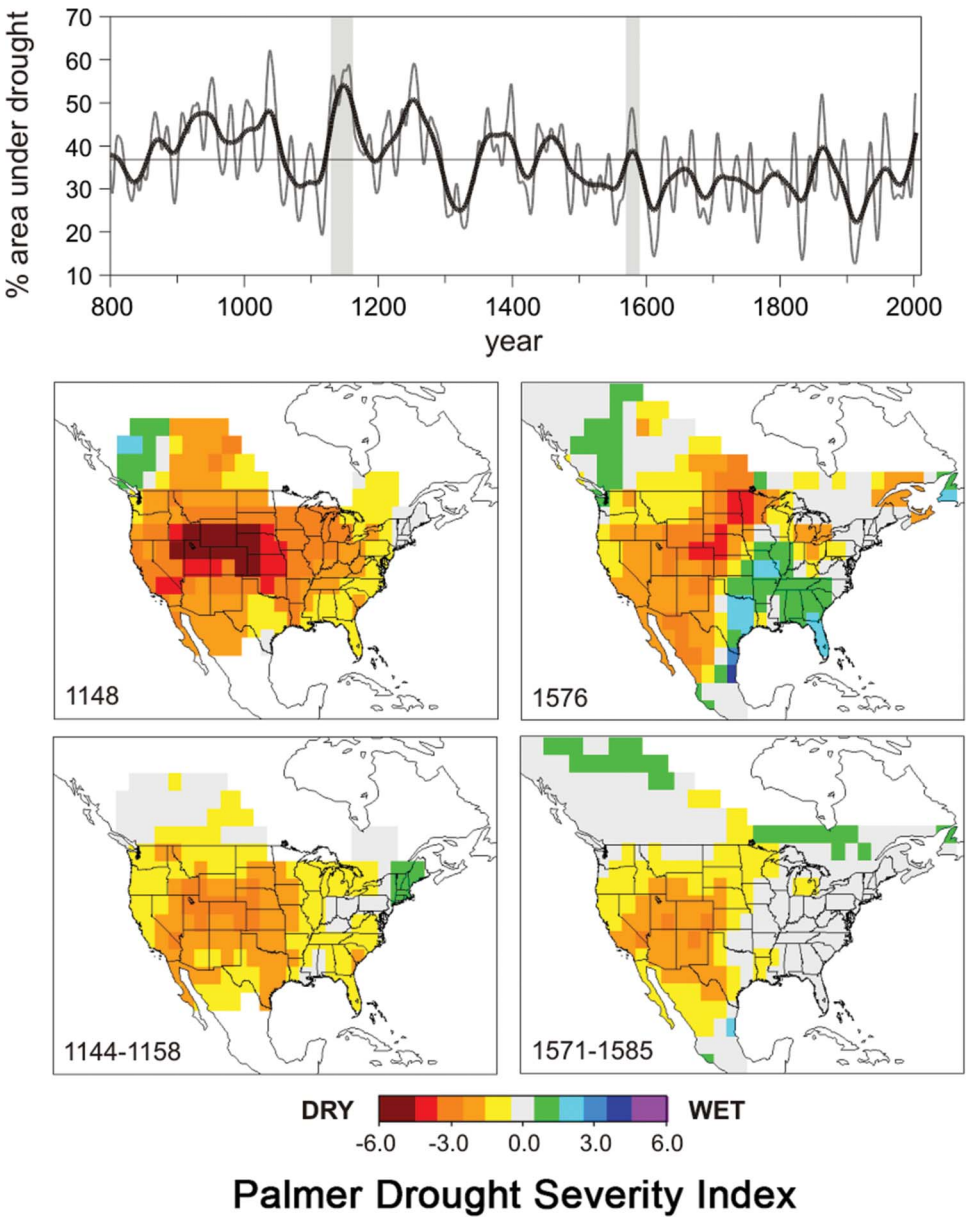

Figure 11. The percent area of the western half of the United States experiencing mild to extreme drought (Palmer Drought Severity Index ≤ -1.0) from the period 800–2000 (graph at top), reconstructed from tree ring data, smoothed with a 60-year spline (heavy line) and a 20-year spline (light line). Note that these long-period filters dampen the apparent magnitude of decadal or shorter droughts. Gray bars indicate periods of drought in the maps below. Data are from Cook et al. (2004). Spatial extent of drought during 12th century megadrought (maps, left) and 16th century megadrought (maps, right). The top two maps show the single worst years within the periods of drought shown in the bottom two maps. This analysis suggests that droughts earlier in the paleoclimatic record (some 600–1200 years ago) were much more severe and extensive than droughts of the 20th century. Data from Cook et al. (2009) and the NOAA Paleoclimatology program (http://www.ncdc.noaa.gov/cgi-bin/paleo/pd08plot.pl). From Peterson et al. (2013b).

tropical cyclone rainfall rates are likely to increase the impacts of these events. In some cases, however, there also will likely also be societal benefits from this increased rainfall, as many regions rely on tropical cyclones to bring the rain needed to maintain regional water resources (Jiang and Zipser, 2010; Lam et al., 2012; Prat and Nelson, 2012).

Drought

Instrumental data indicate that the Dust Bowl of the 1930s and the drought of the 1950s were the most widespread 20th-century droughts in the U.S., while tree-ring data (Figure 11) indicate that the megadroughts during the 12th century exceeded anything in the 20th century in both spatial extent and duration (Peterson et al., 2013b). As stated earlier, model projections of future precipitation generally indicate that northern areas will become wetter, and southern areas, particularly in the West, will become drier (Karl et al., 2009). But to look more directly at drought, projections of future drought were investigated using the NARCCAP regional climate model simulations. Monthly precipitation data were used to compute grid point values of the Standardized Precipitation Index (SPI; McKee et al., 1995).

In the computation of the SPI, the distribution of precipitation amounts is translated into a near-normal (Gaussian) distribution, thus facilitating the representation as standardized anomalies. The values are unitless and can be related to standard anomalies of a normal distribution. One of its features is a user-specified time scale. Typically, the SPI has been calculated for time scales of 1 month to 2 years (NOAA, 2013).

For this study, we computed the 6-month SPI, a time scale that is relevant both to agricultural and water supply applications. Here we define drought as SPI < –1, which will occur on average about 16% of the time, since the SPI is approximately a normal distribution. The change in the frequency of drought (Figure 12) has a distinct north–south gradient. Increases of 6% or more are widespread in the southwestern U.S., with values above 12% in a few locations. This means that the frequency of drought is projected to increase from 16% to 22–28% in this area. By contrast, decreases of up to 6% are simulated in the north-central U.S., meaning that the frequency of drought is projected to decrease to around 10%. This pattern is qualitatively the same in all four seasons, while there are some quantitative differences. The projected changes could arise from both changes in mean precipitation and changes in the persistence of unusually wet or dry periods. However, in this case, the changes in drought are dominated by changes in mean precipitation (not shown). The areas of large projected increases in drought frequency are generally in arid to semiarid regions where current water supplies are very limited.

Increased drought would have major impacts. Drought-induced low water levels can contribute to marked deterioration in water quality due to the lack of dilution of wastewater discharges (Chessman and Robinson, 1987). Comparing conditions of a Nebraska reservoir during drought and normal conditions, Olds et al. (2011) found that water quality was lower during the drought. Specifically, chlorophyll *a* and turbidity were both significantly greater during drought conditions in most months. Dissolved oxygen predominantly decreased during drought conditions, while water temperature did not change. Such changes can occur despite the fact that nitrogen and total organic carbon runoff from farmland can be much lower during drought periods (Endale et al., 2011).

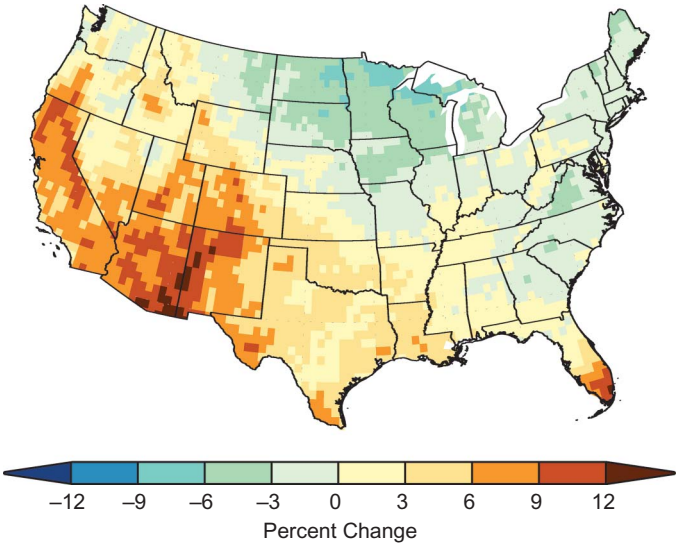

Figure 12. Projected changes in drought. Simulated difference (%) in the number of months with a Standardized Precipitation Index (SPI) value of less than –1 (indicating a drought) for the contiguous U. S., for the 2041–2070 time period with respect to the reference period of 1971–2000 for a high (SRES A2) emissions scenario. These fields are multimodel means for 11 regional climate simulations from the North American Regional Climate Change Assessment Program (NARCCAP). The SPI method normalizes the precipitation distribution such that the percentage of months with SPI < –1 is the nominal value of about 16% for a normally distributed variable. The parameters of the precipitation distribution calculated from the 1971-2000 data are applied to the 2041–2070 period data. These percentages are with respect to the entire distribution. Thus, a value of +10% means that the frequency of occurrence changes from a present climate value of about 16% to a future value of 26%.

Conclusion and Implication

We have high confidence that some of the weather and climate extremes discussed are already changing and are very likely changing due to forcings from anthropogenic greenhouse gases. These include increases in heat waves, decreases in cold waves, and increases in heavy precipitation events. Interannual and longer variability is the main climate signal in the historic record of floods and drought. Yet model projections for future changes in precipitation, which includes increases in the North and decreases in the South, particularly the Southwest, have clear implications for future probabilities of floods and droughts. Hurricanes will likely cause more flooding in the future as both the potential for heavier rain rates increases and sea-level rise makes higher storm surges likely.

The ramification of all these changes on air and water quality are complex but important to incorporate into current planning efforts because climate change is here and now and in our own backyards.

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Appendix: A Note on Hurricanes and Air Quality

This appendix discusses relationships between tropical cyclones and air quality (water-related impacts are discussed elsewhere). Tropical cyclones are relatively transient features of the atmosphere and thus do not typically impact regional air quality in a substantial way. The surrounding regions some distance away from tropical cyclones generally experience clear subsiding air that improves visibility, but this effect is

usually short-lived. A dramatic example of this occurred on September 11, 2001, when subsiding air over New York City, caused in part by Hurricane Erin's presence off the U.S. East Coast, provided ideal Visual Flight Rules conditions for the 911 hijackers, while at the same time Erin provided southward surface wind that carried airborne debris from the collapsed World Trade Center towers away from the most populated urban areas (Kossin et al., 2002). While tropical cyclones have only transient effects on regional air quality, regional air quality can have substantial effects on tropical cyclones, and this is what this appendix focuses on.

Tropical cyclones respond to a number of environmental factors. For example, they tend to form and develop in regions of warm sea surface temperatures (SST) and low vertical wind shear (the change of wind speed or direction with height). One of the better understood environmental measures that has been both theoretically and observationally linked to tropical cyclone development is potential intensity (Emanuel, 1987; Bister and Emanuel, 1997). Potential intensity describes the thermodynamic limit to how intense a tropical cyclone can become, and it depends to a large extent on local SST, as well as on the vertical temperature structure of the atmosphere. How potential intensity responds to past and future changes in greenhouse gas and aerosol concentration is a topic of broad interest and great relevance.

Evidence suggests that SST in the tropics has increased due to increasing greenhouse gases (Gillett et al., 2008; Karoly and Wu, 2005; Knutson et al., 2006; Santer et al., 2006). However, the exact linkage between this SST increase and tropical cyclones remains somewhat uncertain. The reason for this is that the relationship between SST and potential intensity is not unique. For example, raising SST by increasing globally well-mixed greenhouse gas has less effect on potential intensity than raising SST via more regional effects such as aerosol radiative forcing or changing wind speeds (and associated evaporative cooling) over the ocean. This is because the vertical thermodynamic structure of the atmosphere responds to each effect differently (Emanuel et al., 2012).

In the tropical Atlantic, there has been a very substantial increase in both potential intensity and tropical cyclone activity in the past 30–40 years, and aerosols, both natural and anthropogenic, have been implicated as a contributing factor. There is evidence that the warming trend in tropical SST attributed to greenhouse gas forcing has been offset by pollution aerosols, mostly in the form of sulfates (Mann and Emanuel, 2006). This offset occurs through the direct cooling effect of atmospheric dimming, the decrease in solar energy reaching the surface, due to increasing aerosol optical thickness and the indirect cooling effect of aerosols increasing cloud albedo (Baines and Folland, 2007; Booth et al., 2012). The evidence suggests that the reduction of pollution aerosols since the U.S. Clean Air Act and Amendments during and after the 1970s (with further contribution from the European Commission's Air Quality Framework Directive) has reduced the offsetting effects on greenhouse warming, resulting in accelerated tropical SST increases and accompanying increases in tropical cyclone activity. There is also evidence that naturally occurring mineral (e.g., windblown dust from the Sahara Desert) and volcanic aerosols have contributed substantially to the observed tropical SST variability in the Atlantic over the past few decades (Evan et al., 2012; Evan et al., 2011a; Evan et al., 2009), with reduced aerosol loading leading to further increases in tropical Atlantic SST.

In addition to the proposed linkages between pollution aerosols and tropical cyclone potential intensity and activity in the Atlantic, there is evidence that increasing anthropogenic emissions of black carbon and other aerosols in South Asia are linked to a reduction of SST gradients in the Northern Indian Ocean (Chung and Ramanathan, 2006; Meehl et al., 2008), resulting in a weakening of the vertical wind shear in the region. The reduction of SST gradients is caused by the spatial structure of the pollution concentration. Evan et al. (2011b) related the reduced wind shear to the observed increase in the number of very intense storms in the Arabian Sea, including five very severe cyclones that have occurred since 1998, killing more than 3500 people and causing more than $6.5 billion in damages (in 2011 U.S. dollars). In comparison to the Atlantic linkages, which suggest that a *reduction* of pollution aerosols has lead to an increase in tropical cyclone activity, the observed increase in North Indian Ocean tropical cyclone activity has been linked to an *increase* in pollution aerosols.

In addition to interannual to multidecadal forcing of tropical Atlantic SST via radiative dimming, dust aerosols have a large and more immediate in situ effect on the regional thermodynamic and kinematic environment (Dunion, 2011; Dunion and Marron, 2008), and Saharan dust storms—whose frequency has been linked to atmospheric CO_2 concentration (Mahowald, 2007)—have also been linked to reduced strengthening of tropical cyclones (Dunion and Velden, 2004; Wu, 2007). Direct in situ relationships have also been identified between aerosol pollution concentrations and tropical cyclone structure and intensity (Khain et al., 2008; Khain et al., 2010; Rosenfeld et al., 2011). In this case, ingesting continental pollution aerosols affects landfalling storms by enhancing convection and the resulting convective heating in the storm periphery, which causes a weakening of the convection near the storm center and weakens the storm intensity.

In summary, air quality has been linked, via various proposed physical mechanisms, to tropical cyclone variability on timescales from hourly to multi-decadal. This introduces additional uncertainty into numerical projections based on future emission scenarios, in which aerosol projections are known to be highly uncertain (Forster et al., 2007; Haerter et al., 2009).

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