MONITORING AND UNDERSTANDING CHANGES IN HEAT WAVES, COLD WAVES, FLOODS, AND DROUGHTS IN THE UNITED STATES

State of Knowledge

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Some of the long-term changes in weather and climate extremes have occurred as expected in the warming climate, but trends are not all uniform across the United States nor easily detected amidst multiyear and decadal variations.

The Global Change Research Act of 1990 requires the U.S. government to prepare a report that integrates, evaluates, and interprets scientific analyses of effects of global climate change on both human and natural systems in the United States. The U.S. National Climate Assessment (www.globalchange.gov/what-we-do/assessment) must therefore address extremes because not only are extremes changing (e.g., Field et al. 2012; Coumou and Rahmstorf 2012) and anthropogenic climate change has a role in altering the probabilities of some of the extreme events (Peterson et al. 2012) but extreme events drive changes in natural and human systems much more than average climatic conditions (Peterson et al. 2008).

However, the domain of extremes is so broad, ranging from tornados less than 1 km across and lasting only a few minutes to 1,000-km-wide droughts lasting many months, and the scientific literature is so diverse that it is not easy for the assessment writing teams to accurately cover all extremes. Therefore, to provide technical input to the U.S. National Climate Assessment writing team, four workshops were held where leading scientists in the field came together to assess or, more accurately, to determine how best to assess the state of the science in understanding the decadal- to century-scale variability and changes in various types of extreme events. After the workshops, the meeting participants produced papers synthesizing the state of the science on their set of extremes.

The first workshop focused on severe local storms, including tornadoes and extreme precipitation (Kunkel et al. 2013). The third workshop examined extratropical storms, winds, and waves (Vose et al. 2013, manuscript submitted to *Bull. Amer. Meteor. Soc.*). The fourth workshop assessed historical and projected climate extremes in the United States simulated in phase 5 of the Coupled Model Intercomparison Project models (Wuebbles et al. 2013, manuscript submitted to *Bull. Amer. Meteor. Soc.*). While our workshop, the second workshop, focused on the large-scale phenomena of heat waves, cold waves, floods, and drought and served as the basis for this paper, it also allowed the experts to discuss what information is required and what additional analyses we should preform so that we could incorporate their results into this article. As the peer-reviewed literature on these phenomena use many different approaches in assessing these extreme events, our paper as well must use different methodologies where appropriate.

Because the National Climate Assessment has different writing teams focusing on different regions (see Fig. 1), where appropriate this paper describes the geographic differences in the long-term behavior of heat waves, cold waves, floods, and droughts across the United States. While most of the information below comes from either our own or previous peer-reviewed publications' quantitative analyses, there was one subjective assessment that the workshop facilitated: rating the state of the understanding of the physical factors that cause these extremes to change and the adequacy of the data to accurately reveal long-term variability and change in these extremes, in comparison to each other and in comparison to the extremes assessed in the other workshops.

Defining exactly what constitutes an extreme varies with the phenomenon. Some phenomena, such as hurricanes, tornadoes, floods, and droughts, are by their very definitions extreme events partly because they are rare and have high impacts. However, other extremes, such as heavy precipitation, are simply points on the tails of the distribution of the observations. Exactly how far out on the tail of the distribution one should go is often determined by the goal of the analysis. For example, while a 20-yr return period extreme may have far more societal relevant impacts than an extreme that might occur every year or two, if one is seeking to detect changes in extremes in a part of the world with only 50 yr of available daily data, then 20-yr return period events would provide too few data points for robust trends. Zwiers et al. (2012) provides more context on what constitutes an extreme.

HEAT WAVES AND COLD WAVES.

Introduction. Episodes of extreme heat and cold can have serious societal, agricultural, economic, and ecological impacts across the United States, with heat being the number one weather-related killer (National Weather Service 2012; Borden and Cutter 2008). In addition to temperature, high humidity can increase the impacts of heat waves, while high winds can increase the impacts of cold waves (Sheridan and Kalkstein 2004; Steadman 1984; Stocks et al. 2004; Ames and Insley 1975). Many agricultural products exhibit direct temperature threshold responses (e.g., Schlenker and Roberts 2009; White et al. 2006) and can be indirectly affected through threshold responses of agricultural pests (Diffenbaugh et al.

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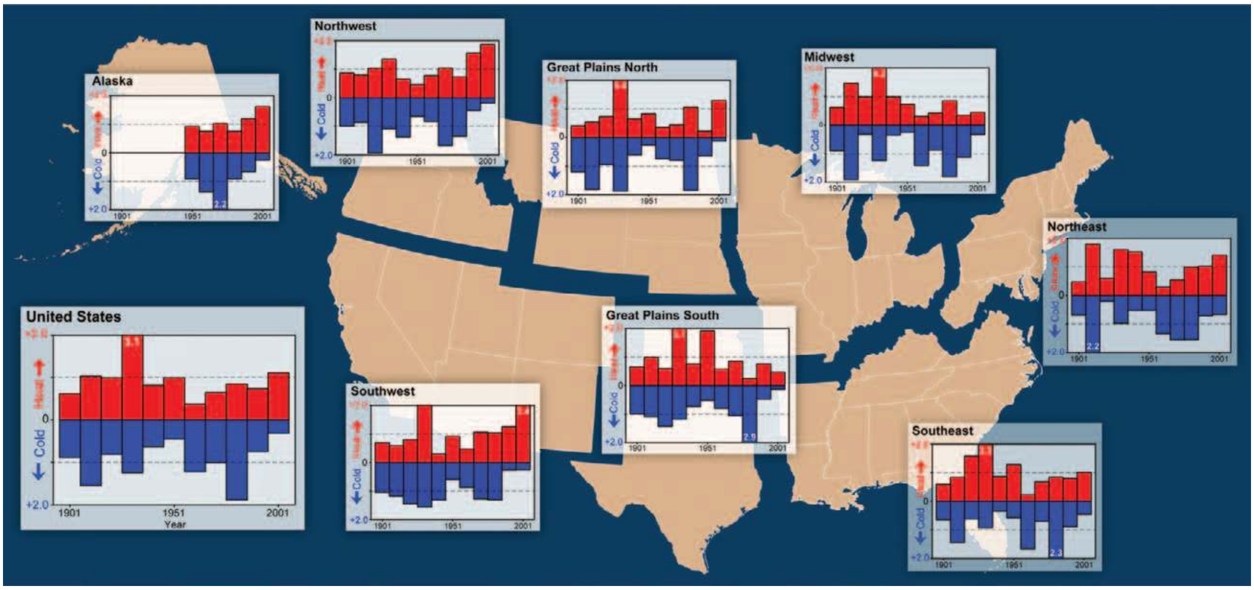

Fig. 1. Time series of decadal-average values of heat wave (red bars) and cold wave (blue bars) indices. These indices are a normalized (to an average value of 1.0) metric of the number of extreme temperature events for spells of 4-day duration. An event is considered extreme if the average temperature exceeds the threshold for a 1- in 5-yr recurrence. The calculations are based on a network of 711 long-term stations with less than 10% missing temperature values for the period 1895–2010. The horizontal labels give the beginning year of the decade. Recent decades tend to show an increase in the number of heat waves and a decrease in the number of cold waves but, over the long term, the drought years of the 1930s stand out as having the most heat waves. See the SM for details on the daily data used in this analysis and procedures used to calculate the indices.

2008, and references therein). Ecological responses include limitation of invasive species by severe cold (Walther et al. 2002; Firth et al. 2011), large-scale forest biomass decline in response to severe heat (Toomey et al. 2011), and bleaching of corals by high ocean temperatures (Brown 1997). Physical characteristics and classification of the main types of heat and cold waves are given in the supplementary material (SM; available online at http://dx.doi.org/10.1175/BAMS-D-12-00066.2) in Table ES1.

Heat and cold waves are typically defined as events exceeding specified temperature thresholds over some minimum number of days. Chosen thresholds may be statistical or absolute and in the case of the latter are geographically and sector dependent [e.g., the occurrence of nighttime lows > 80°F (~27°C) in Chicago, Illinois, being far more significant than in Houston, Texas]. Robust analysis of these events over time requires daily maximum and minimum temperature data from stations with records of sufficient length, quality, completeness, and temporal homogeneity. Homogeneity of the daily temperature record is an especially difficult challenge because of stations experiencing varying degrees of change over time in location, instrumentation, observing practices, and siting conditions. Details regarding the U.S. station networks used in this analysis, along with additional discussion of the issues and caveats involved in the use of daily temperature data, are given in the SM.

Observed changes. Figure 1 illustrates temporal changes in the number of 1- in 5-yr magnitude heat and cold waves for the conterminous United States and Alaska.[1] For the conterminous United States (Fig. 1: graph labeled "United States"), the highest number of heat waves occurred in the 1930s, with the fewest in the 1960s. The 2001–10 decade was the second highest but well below the 1930s. Regionally, the western regions (including Alaska) had their highest number of heat waves in the 2000s, while the 1930s were dominant in the rest of the country. For cold wavenumbers, the national-average value was highest in the 1980s and lowest in the 2000s. The lack of cold waves in the 2000s was prevalent almost everywhere.

The changes in the more extreme 20-yr return values of four types of events are shown in Fig. 2 for

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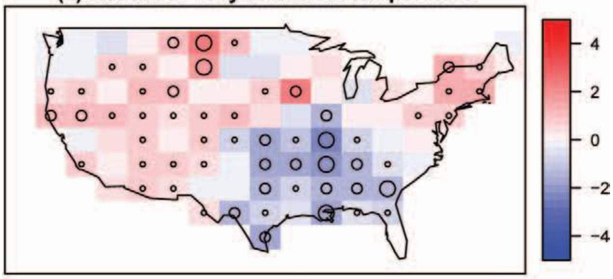
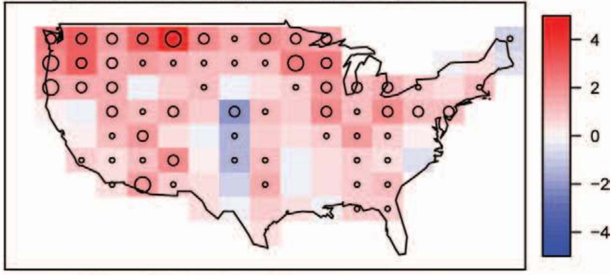
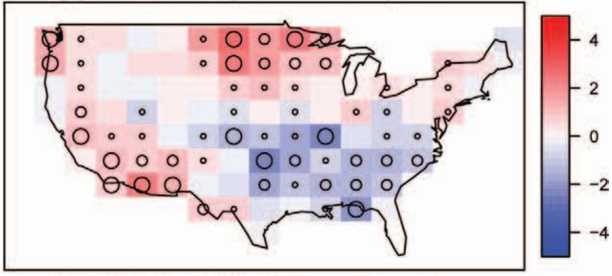
[1] Hawaii is not included in our analysis because its tropical climate has a relatively small temperature variance that does not produce impacts like those found over the conterminous United States and Alaska. Note the Alaskan time series begin in the 1950s.

the period 1950–2007 (2007 return values minus 1950 return values) using the HadEX Global Climate Extremes Indices database (Alexander et al. 2006), obtained from a time-dependent "peaks over threshold" model described in the SM. The "warming hole" in the Southeast United States, related to the current warm tropical Pacific phase of the Pacific decadal oscillation (PDO; Meehl et al. 2012), is evident in the high tails of both maximum and minimum temperature (Figs. 2a,c). In fact, the trends for the high tails of the temperature distributions are similar to the trends in the mean of these distributions (Brown et al. 2008). The low tails, however, behave differently with mostly positive trends in the coldest maximum temperature values (Fig. 2b) and positive trends in the coldest minimum temperature values (Fig. 2d). While these findings are based on singular daily maximum and minimum temperatures and therefore differ from the heat wave/cold wave criteria used in Fig. 1, they reflect changes in extremes that are often part of multiday events (Furrer et al. 2010). These results parallel the results of Meehl et al. (2009), who found that the current observed ratio of record high maximum temperatures to record low minimum temperatures averaged across the United States is about 2 to 1.

Current state of understanding. At the global scale, trends in extreme temperature events have been found to be outside the bounds of unforced natural variability, leading to a conclusion that they are anthropogenically driven (Christidis et al. 2005; Field et al. 2012; Coumou and Rahmstorf 2012). However, at most subcontinental scales (including the United States), current anthropogenic effects are not sufficient to exceed the effects of natural modes of variability on observed trends in temperature extremes (Brown et al. 2008). Indeed, using decadal variations in the number of conterminous U.S. heat and cold waves (Fig. 1) as one indicator of temperature extremes, it is interesting to note that these variations bear limited resemblance to the annual-average conterminous U.S. temperature series of Menne et al. (2009) (their Fig. 12; reproduced in the SM as Fig. ES1), which are considered to be anthropogenically driven since the mid-1900s (Hegerl et al. 2007). For example, Figs. 1 and ES1 each indicate extreme warmth in the 1930s (especially for maximum temperature in Fig. ES1),


(a) Hot tail of daily maximum temperature


(b) Cold tail of daily maximum temperature


(c) Hot tail of daily minimum temperature

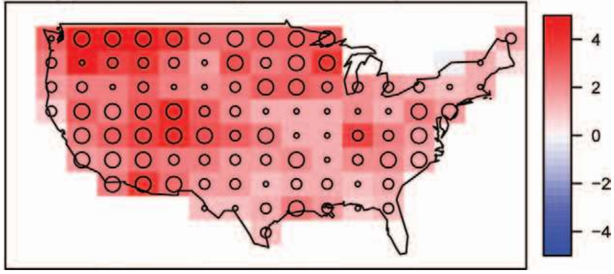

(d) Cold tail of daily minimum temperature

Fig. 2. Change over 1950–2007 in estimated 20-yr return value (°C) for (a) hot tail of daily maximum temperature, (b) cold tail of daily maximum temperature, (c) hot tail of daily minimum temperature, and (d) cold tail of daily minimum temperature. Results are based on fitting extreme value statistical models with a linear trend in the location parameter to exceedances of a location-specific threshold (greater than the 99th percentile for upper tail and less than the 1st percentile for lower tail). Circles indicate *z* score for the estimated change (estimate divided by its standard error), with absolute *z* scores exceeding 1, 2, and 3 indicated by open circles of increasing size. (Further details on *z* scores and statistical significance are presented in the SM.) The greatest warming is in the cold tail of minimum temperatures in (d). The hottest values of both daily maximum temperatures in (a) and minimum temperatures in (c) have been decreasing in the Southeast. As this analysis was based on anomalies with respect to average values for that time of year, hot minimum temperature values, for example, are just as likely to occur in winter as in summer.

but Fig. ES1 does not hint at the 1980s experiencing the most cold waves of any decade (Fig. 1). However, the post-2000 portion of the minimum temperature series in Fig. ES1 (the warmest stretch in the record) does correspond with the 2000s in Fig. 1, showing the smallest number of cold waves of any decade.

Atmospheric moisture plays an important role in heat waves. The impact of heat waves on humans is exacerbated by high humidity (e.g., the deadly 1995 Chicago heat wave; Karl and Knight 1997). Gaffen and Ross (1998) found significant increases in apparent temperature over parts of the United States from 1949 to 1995. Extremely high dewpoint temperatures recently observed in parts of the United States (e.g., NOAA 2011) can lead to extremely warm nights. Conversely, some of the most extreme, prolonged, and high-impact heat waves in the United States are bolstered by positive, reinforcing feedbacks related to low-humidity and drought conditions (e.g., over the central United States in summer 2012; NCDC 2012). Such heat/drought linkages are also discussed in the subsection on the current state of understanding in the "Droughts" section, while more detailed characteristics of atmospheric/land surface processes relating to both U.S. heat and cold waves are presented in Table ES1 in the SM.

Evidence indicates that the coldest air masses in North American source regions (mainly arctic and subarctic Canada) are warming on multidecadal time scales (Kalkstein et al. 1990; Hankes and Walsh 2011). While the Pacific decadal oscillation is known to affect Alaskan temperatures (Hartmann and Wendler 2005), warming of these source regions likely provides additional explanation for the decreasing trends in cold waves since the 1970s in Alaska and may relate to similar trends over the Northwest and Southwest (Fig. 1), as only the coldest air masses are typically able to spill westward across the Rocky Mountains. East of the Rockies, the highest numbers of cold waves occurred in the 1980s. Strong warming of the coldest nights experienced over much of the United States since 1950 (Fig. 2d) is consistent with the aforementioned warming of the North American cold airmass source regions.

FLOODS. *Introduction.* 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). These changes can occur in tandem and make it difficult to determine the relative importance of each factor as drivers of observed changes in river flooding behavior. Given the large changes that most of the watersheds across the United States have undergone during the twentieth century (e.g., Villarini et al. 2009a), ours and other analyses have taken measures to assure that results are not driven by changes in land use or water management.

Further compounding analyses' complexity, watersheds have memory (due to moisture storage), so that extreme wetness or dryness can influence flood behavior over many years. Because of natural climate variability and basin memory, there is a potential for trendlike behavior that lasts multiple decades but when viewed in a longer context is only a single limb of an oscillation or part of a transient change (see Lettenmaier and Burges 1978; Cohn and Lins 2005; Koutsoyiannis and Montanari 2007). While century-scale records can help mitigate but not eliminate this issue, they also limit the ability to assess the role of drivers that may only dominate later in the record. For example, the effects of human influence on global temperature diverge from natural variability only after about 1950 (Hegerl et al. 2007).

Observed changes. Changes in the magnitude of peak annual river floods are shown in Fig. 3a for the subset of all watersheds with records on the order of 100 years that have experienced little or no land-use or water management changes. While much of the United States shows little or no change in flooding, some areas have spatially coherent changes. Flood magnitudes have been decreasing in the Southwest. Long-term data show an increase in flooding in the northern half of the eastern prairies and parts of the Midwest, especially when examined over the last several decades. Land management practices could be a contributing factor (e.g., Zhang and Schilling 2006; Schilling et al. 2008; Villarini et al. 2011), and this is an area with observed oscillatory behavior at a time scale on the order of a century (see Shapley et al. 2005; Vecchia 2008). Another area where increased flooding has been well documented is from the northern Appalachian Mountains to New England (Collins 2009; Villarini and Smith 2010; Smith et al. 2010; Hodgkins 2010; Hirsch and Ryberg 2012).

Current state of understanding. Days with heavy precipitation have been increasing significantly across the eastern United States, particularly in New England (Karl et al. 2009; Kunkel et al. 2013). Interestingly, this trend is not strongly related to changes in river flooding. Possible reasons for this mismatch include that flooding in most river basins larger than 1000 km^2 generally respond to longer-duration precipitation events and because some of the changes in heavy precipitation occur during seasons that generally do not produce floods (e.g., Small et al. 2006). For example, an area such as the northern Great Plains, where peak flooding most often occurs during spring snowmelt, tend to have their heaviest daily rainfall events during summer convective storms. Additionally, some of the greatest floods in the last few decades, such as the great upper Mississippi basin flood of 1993 (Wahl et al. 1993), have been in response to seasonal and longer extreme events. However, examination of changes in long-term flooding (Fig. 3a) and corresponding changes in total annual precipitation (Fig. 3b) does reveal regional-scale similarity.

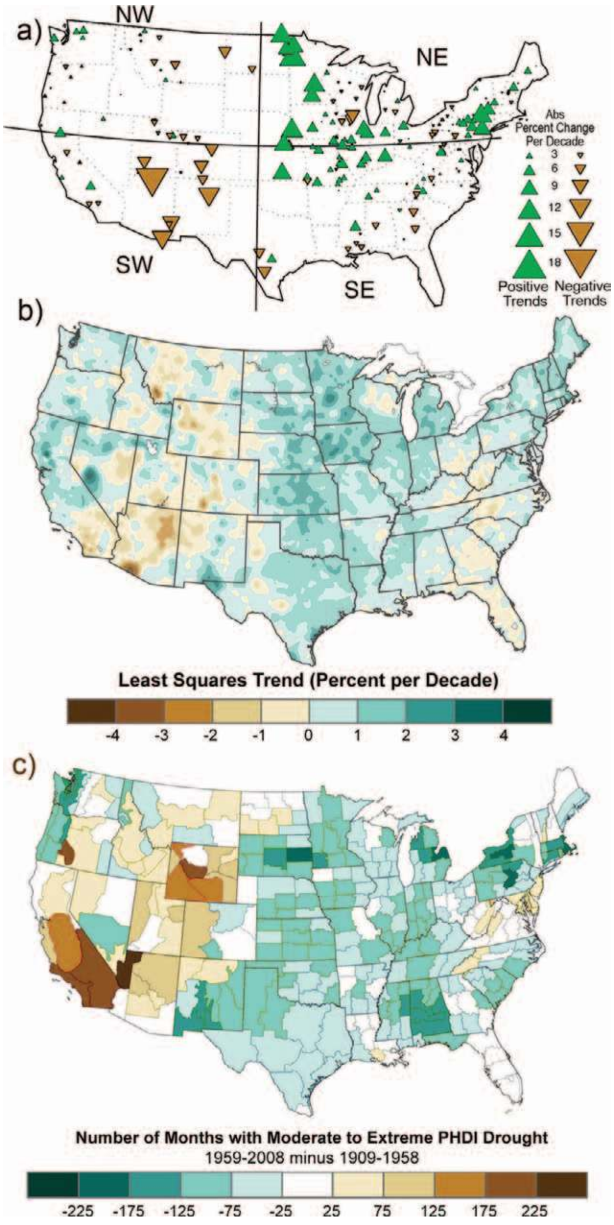


Fig. 3. Geographic distribution of century-scale changes in (a) flooding, (b) precipitation, and (c) droughts. In (a), the triangles are located at 200 stream gauges, which have record lengths of 85–127 years. The selection of these sites is described by Hirsch and Ryberg (2012). The color and size of the triangles are determined by the trend slope of a regression of the logarithm of the annual flood magnitude vs time for the entire period of record at the site, ending with water year 2008. In (b), trends in total annual precipitation as percentages for a 100-yr period end the same year as the flood data (2008) shown in (a). Precipitation data are from Global Historical Climatology Network (GHCN)-Daily (Menne et al. 2012) and Snowpack Telemetry (SNOTEL; Serreze et al. 1999) data. In (c), the number of months with the Palmer Hydrological Drought Index (PHDI) ≤ –2.0 (moderate to extreme drought) in the second half of the same 100-yr period used in (b) minus the first half (plotted by climate division, which is the source dataset) are shown. Note there are regional similarities between the figures, such as increases in floods and precipitation in the northeastern Great Plains and drying in the Southwest, but there is not a one-to-one correspondence.

For some regions of the United States where snowpack is an important component of the hydrologic system, there is evidence for earlier melt and changes in the rain-to-snow ratio (see Dettinger and Cayan 1995; Hodgkins et al. 2003). These changes may be influential in changing river flood behavior, but their nature could be either decreases or increases in flood magnitudes, depending on watershed characteristics. The Southwest United States shows a general decrease in flood magnitudes, possibly attributable to general drying and diminished snowpack that can be related to changes in greenhouse forcing (Hirsch and Ryberg 2012; Milly et al. 2005). For California in particular, narrow bands of concentrated water vapor transport referred to as atmospheric rivers drive many of the catastrophic floods, but more work needs to be done to reliably estimate their potential change (Dettinger 2011). While precipitation and flooding have been increasing in the northern half of the eastern prairies in recent decades, general circulation models do not show this as an area expected to have a substantial increase in runoff in the twentieth-century hindcast or the twenty-first-century forecast (Milly et al. 2005, 2008).

Total annual precipitation for the United States has increased on average about 5% over the past 50 years (Karl et al. 2009). Projections for future precipitation are less certain than projections for future temperature but generally indicate that northern areas are likely to become wetter and southern areas, particularly in the Southwest, are likely to become drier (Karl et al. 2009). However, when considering the issue of future river flood hazard changes, it is important to recognize that urban and rural land-use impacts and water management impacts have significant influence on flood behavior (e.g., Villarini et al. 2009b; Vogel et al. 2011; Hirsch 2011; Zhang and Schilling 2006; Schilling et al. 2008; Villarini et al. 2011). In addition, while there have been large increases in flood damages over the past century, one key driver of that is growth in the economic activity situated in high flood hazard areas (Pielke and Downton 1999; Pielke 1999), which appears to be continuing.

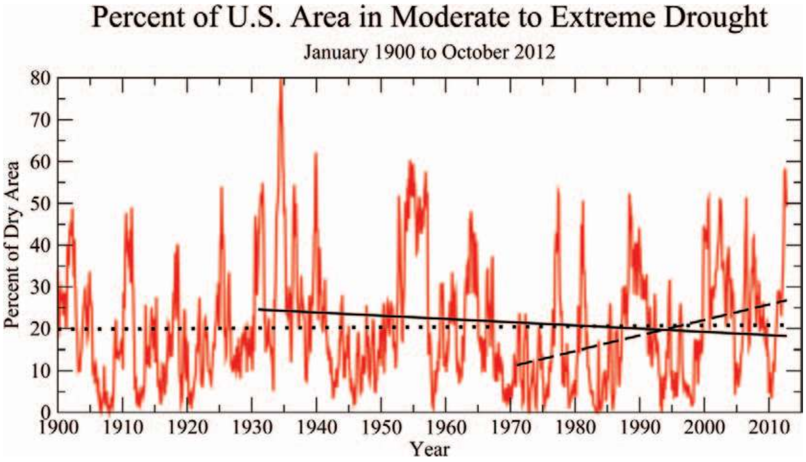


Fig. 4. The percent area of the contiguous United States experiencing moderate to extreme drought [Palmer drought severity index (PDSI) ≤ –2.0] from January 1900 to October 2012 (red curve). Widespread persistent drought occurred in the 1930s (central and northern Great Plains, Northwest, and Midwest), 1950s (southern Great Plains and Southwest), 1980s (West and Southeast), and the first decade of the twenty-first century (West and Southeast). The dotted line is a linear regression over the period of record (linear trend = +0.09% decade^{-1}), the solid line is for January 1931–October 2012 (–0.78% decade^{-1}), and the dashed line is for January 1971–October 2012 (+3.70% decade^{-1}).

DROUGHTS.

Introduction. Drought is a very complex phenomenon that is difficult to define and measure. Drought is best represented by indicators that quantitatively appraise the total environmental moisture status or the imbalance between water supply and water demand, usually involving characteristics such as duration, intensity, size of the area affected, and impacts (World Meteorological Organization 1992; American Meteorological Society 1997; Heim 2002; Mishra and Singh 2010; Zwiers et al. 2011). As multiple climate variables affect drought, drought-related datasets and products are derived from a broad set of variables. Drought indices are based on precipitation data (e.g., McKee et al. 1993; Guttman 1998), precipitation and temperature data (e.g., Palmer 1965; Guttman 1998; Dai et al. 2004; Heim 2002), stream discharge records (Heim 2002; Flieg et al. 2006; Zwiers et al. 2011), and model-based soil moisture indicators (e.g., Koster et al. 2009) and other modeling techniques (e.g., Gutzler and Robbins 2010; Kao and Govindaraju 2010) and often have a particular focus such as agricultural droughts or hydrological droughts.

Observed changes. The PHDI (a monthly precipitation and mean temperature drought indicator based on computations using 1931–90 for the calibration period) was analyzed to assess observed changes in drought for the period 1900–2011. Based on the PHDI, each decade has experienced drought episodes that covered 30% or more (by area) of the contiguous United States (Fig. 4). The 1930s and 1950s had the worst droughts, with 31.7% and 15.6%, respectively, of the the U.S. experiencing their driest period on record. By comparison, during the first decade of the twenty-first century (2001–10) 12.8% and for 2011 8.3% of the U.S. experienced their record drought. Major droughts typically last two to three years though sometimes considerably longer. In 2012, all-time monthly driest records (based on statewide-average precipitation) occurred for six states and the second driest records occurred for eight other states, with drought expanding during the summer to cover 39.0% of the contiguous United States (PDSI ≤ –3.0), which is the largest extent since the 1950s (Karl et al. 2012).

Examination of trends and variability of hydroclimatic conditions in the conterminous United States during the past century indicates that there has been a general drying across the western United States during recent decades (Fig. 3c). An analysis, using the nonparametric Kendall's tau test (after McCabe and Wolock 2002), of trends in hydrological droughts in the conterminous United States, as represented by annual minimum streamflow (Fig. 5), indicates that there have been long periods of trends toward wetter conditions and other periods with trends toward drier conditions. For example, trends toward wetter

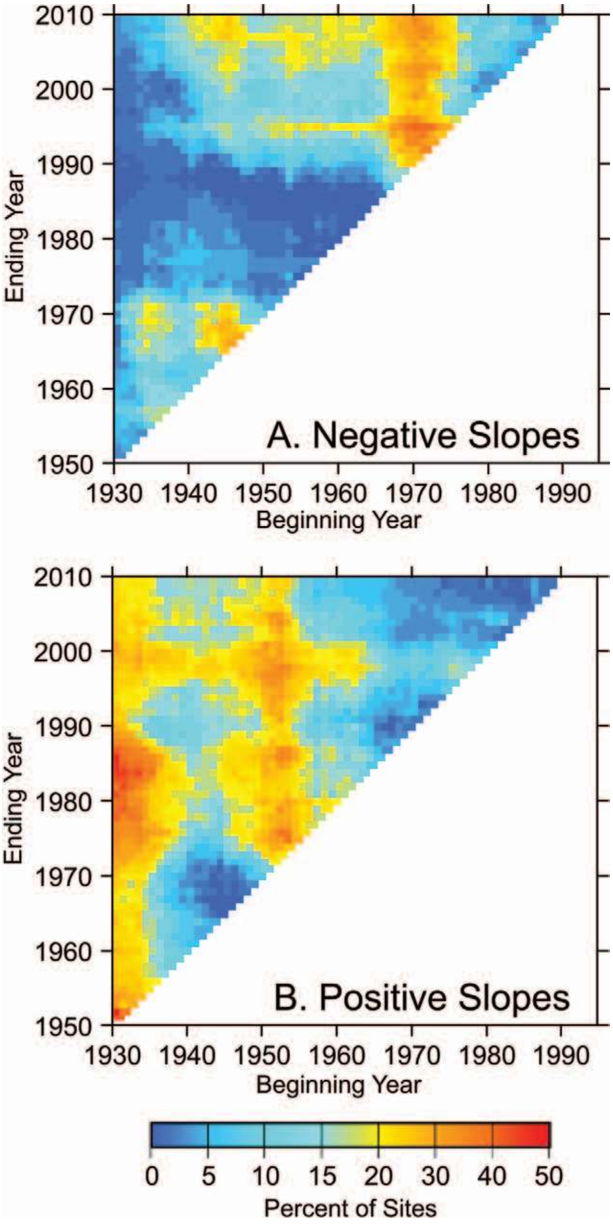


Fig. 5. The percent of streamflow sites (of 320 sites in the conterminous United States) with statistically significant ($p \leq 0.05$) (top) negative slopes and (bottom) positive slopes of annual minimum flows for periods of varying lengths (at least 20 years in length), with beginning and ending years from 1931 to 2010. The time series from each site was evaluated for trends using the nonparametric Kendall's tau, after the analysis in McCabe and Wolock (2002). The *x* axis shows the beginning year of the trend analysis, while the *y* axis shows the ending year. The warmer colors (yellows to reds) indicate a higher percentage of sites with the indicated slopes. This figure highlights the importance of the start and end year in trend analyses. Trend analyses that start during the droughts of the 1930 and 1950s tend to show decreasing droughts (a high percentage of sites with positive trends in streamflow), while trend analyses starting in the 1970s generally indicate increasing drought.

conditions dominated periods beginning during the drought years of the 1930s and 1950s and trends toward drier conditions dominated periods beginning near 1970 and continuing to the present.

By using regression techniques to relate tree ring and other paleoclimatic data to instrumental data (e.g., temperature, precipitation, and PDSI), drought records can be extended back many centuries prior to the beginning of instrumental data (Fig. 6). The area under drought in the western half of the United States is estimated to have averaged 38% from 800 to 2005, but from 900 to 1300 the area increased to an estimated 42.4%, a significantly larger area than during the twentieth century (30%) (Cook et al. 2004), suggesting that the West has seen much more severe and extensive droughts in prior centuries than have occurred during the twentieth century. The 900–1300 period encompassed the most prolonged and severe drought on the Colorado River (nearly six decades in the mid-twelfth century) and one of the most severe droughts on the Sacramento River (Meko et al. 2001, 2007). The droughts of the twelfth and thirteenth centuries exceed anything in the twentieth century in both spatial extent and duration. Less spatially extensive but still extreme, the droughts in the late sixteenth century impacted regions that ranged from northern Mexico and the Intermountain West to the Mississippi Valley and the southeastern United States (Stahle et al. 2000; Cook et al. 2007).

Current state of understanding. Several physical processes contribute to droughts, with varying importance depending on time scale, region, and season. Most droughts are associated with persistent anticyclones, with poleward expansion of the subtropical dry zone projected to play an increasingly important role in the southwestern United States in the future (Seager et al. 2007; Seager and Vecchi 2010). Short-term droughts are primarily related to atmospheric circulation patterns (Lorenz and Hartmann 2006; Schubert et al. 2011). Forcings by anomalous sea surface temperatures (SSTs) have played an important role in many extreme droughts as well as megadroughts (Woodhouse and Overpeck 1998; McCabe et al. 2004; Cook et al. 2009b). Pacific SST anomalies associated with El Niño–Southern Oscillation (ENSO) or the PDO most often provide the dominant forcing, although Indian and Atlantic Ocean SSTs have also been shown to have an effect (Hoerling and Kumar 2003; Schubert et al. 2004a,b; Hoerling et al. 2009; Cook et al. 2011a,b). Climate models forced by observed SSTs indicate that drought conditions are more likely to occur over most of the continental United States when the middle and eastern tropical Pacific is colder than normal (La Niña) or when the North Atlantic is warmer than normal (positive Atlantic multidecadal oscillation), with the greatest likelihood of drought occurring when both of these conditions are present (Schubert et al. 2009). The same models forced by a global warming trend SST pattern produce overall warming over land with substantial regional variations but no coherent precipitation response.

Changes in evapotranspiration typically act as a feedback that can increase drought severity and duration (Atlas et al. 1993; Lyon and Dole 1995; Fischer et al. 2007a,b), depending on vegetation and soil moisture states, which in turn depend on prior climate conditions, season, and region (Durre et al. 2000; Koster et al. 2011). With prolonged drought, reduced evapotranspiration leads to lower latent heat fluxes, increased sensible heat fluxes and higher surface temperatures, and intensifying summer heat waves (Lyon and Dole 1995; Black et al. 2004). Meteorological drought occurring in a warmer climate can also lead to increased tree mortality, with additional ecosystem–climate feedbacks (Breshears et al. 2005). Land-use practices and the effects of dust aerosols can also have important feedback roles, notably during the 1930s Dust Bowl (Cook et al. 2009a), indicating that multiple human influences must be considered when examining the causes of drought (Pielke et al. 2011). Overall warming can intensify hydrological droughts and alter runoff timing from snowmelt (Barnett et al. 2008; Cayan et al. 2010).

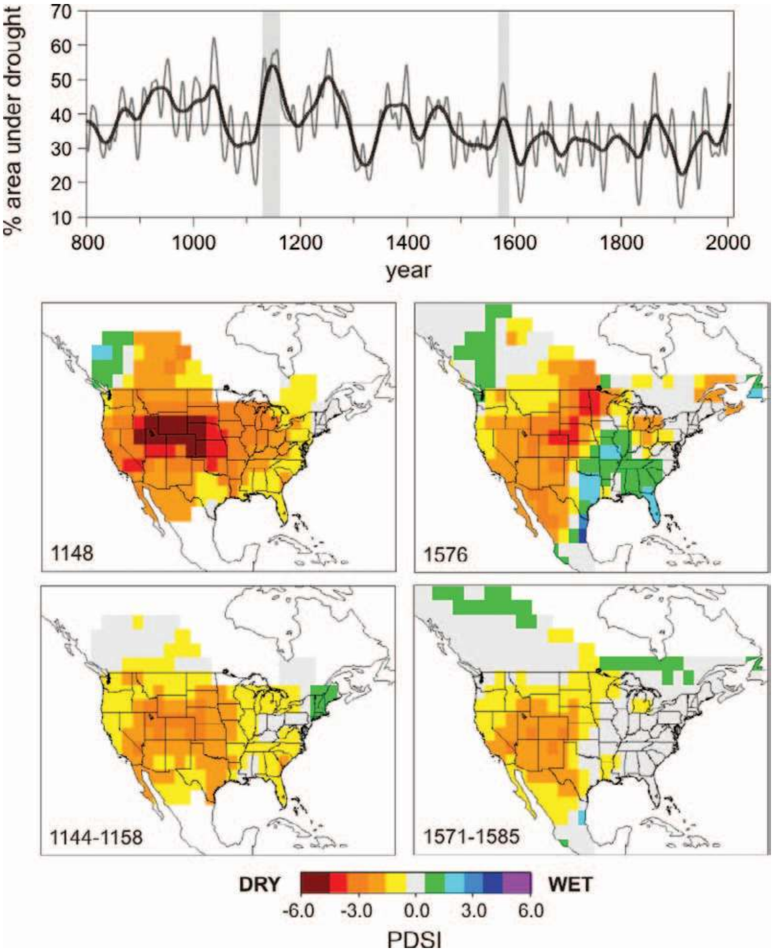


Fig. 6. The percent area of the western half of the United States experiencing mild to extreme drought (PDSI ≤ –1.0) from 800 to 2000 (graph at top), reconstructed from tree ring data, smoothed with a 60-yr spline (heavy line) and a 20-yr spline (light line). Note that these long-period filters dampen 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). Maps show the spatial extent of drought during the (left) twelfth- and (right) sixteenth-century megadroughts, showing (top) the single worst years within (bottom) the periods of drought. 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 twentieth century. Data are from Cook et al. (2009b) and the NOAA Paleoclimatology Program (www.ncdc.noaa.gov/cgi-bin/paleo/pd08plot.pl).

CONCLUSIONS. Four key types of climate extremes (i.e., heat waves, cold waves, floods, and droughts) were assessed. The data indicate that over the last several decades heat waves are generally increasing, while cold waves are decreasing. While this 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 warming observed over the United States. The drought years of the 1930s had the most heat waves, while the 1980s had the highest number of cold waves. River floods do not show uniform changes across the country; flood magnitudes as represented by trends in annual peak river flow have been decreasing in the Southwest, while flood magnitudes in the Northeast

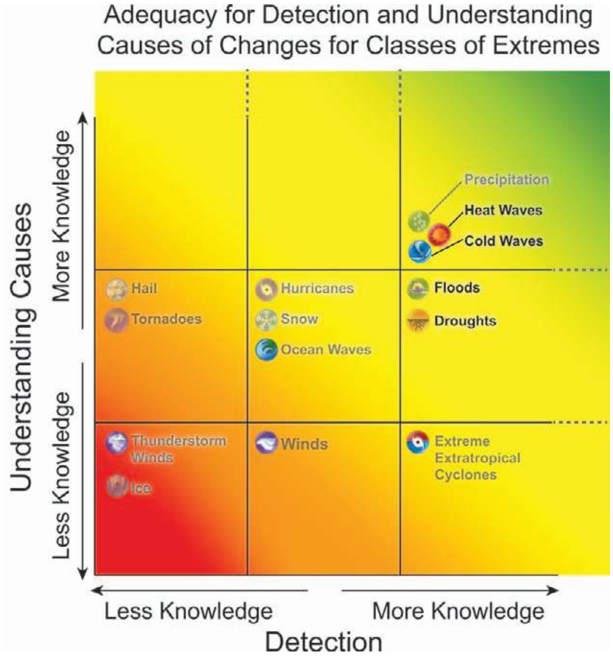


FIG. 7. Detection and attribution of changes in extremes depend on both scientists' physical understanding of the factors that not just cause a particular extreme but would cause the intensity or frequency of that extreme to change over time and the quality and quantity of the data. The first workshop produced an assessment of these factors for seven different extremes (Kunkel et al. 2013) and the third workshop produced an assessment of these factors for an additional three (Vose et al. 2012, manuscript submitted to *Bull. Amer. Meteor. Soc.*), which are shown with gray text. Using this same scale, we have inserted heat waves, cold waves, floods, and drought. The *x* axis refers to the adequacy of data to detect trends, while the y axis refers to scientific understanding of what causes those trends. The dashed lines on the right side and top of the graph imply that the knowledge about the phenomena is not complete.

and north-central United States are increasing. Confounding the analysis of trends in flooding is multiyear and even multidecadal variability likely caused by both large-scale atmospheric circulation changes as well as basin-scale "memory" in the form of soil moisture. Droughts too have multiyear and longer variability. Instrumental data indicate that the Dust Bowl of the 1930s and the 1950s drought were the most widespread twentieth-century droughts in the United States, while tree ring data indicate that the megadroughts over the twelfth century exceeded anything in the twentieth century in both spatial extent and duration.

Figure 7 summarizes the authors' assessments of two key aspects impacting the state of the science with regard to long-term changes in heat waves, cold waves, floods, and droughts. The first is how well scientists understand the causes of changes in these extremes. Of the four extremes considered, the causes of changes in heat waves and cold waves are better understood than the causes of changes in floods and droughts. However, there is still a far better understanding of the causes of long-term changes in droughts than, for example, changes in thunderstorm winds. The second aspect is the adequacy of the data for detecting and understanding the causes of changes in the extremes. In this case, the data to assess changes in all four of these extremes are quite good compared to other extremes, despite the very different types of data. For example, while there is a large amount of precipitation data, which are the primary source of information for most drought indices, precipitation data do not directly measure drought as other factors, such as temperature, have impacts on droughts as well. However, the more limited streamflow data do directly measure river flooding.

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