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An overview of weather and climate extremes – Products and trends

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ABSTRACT

This paper provides an overview of trends in weather and climate extremes as presented at a recent WMO Symposium on global food security and biodiversity. Analyses and conclusions about weather and climate extremes are best based on daily data, and an internationally agreed-upon set of daily extremes indices has been devised for this purpose. Characteristics of climate data sets which are necessary for an adequate analysis of changes or trends in extremes are identified. Analyses summarized in the Intergovernmental Panel on Climate Change Fifth Assessment Report indicate that, since the 1950s, there has been a trend toward fewer cold days and nights and more warm days and nights globally, increasing heavy precipitation events in many parts of the world, and regional trends (both increasing and decreasing) in drought and dryness extremes. A more detailed discussion of indices for the USA illustrates features of some of these trends, including a significant change in trends of extremes which occurred in the 1970s. There is considerable decadal variability in drought area in the contiguous USA, and the long-term trend depends on the beginning and ending years chosen, but there has generally been an increasing trend in drought area over the 20th to 21st centuries and over the last four decades. The annual percent area of the USA experiencing greater-than-normal number of days with (without) precipitation has increased (decreased) over the 20th to 21st centuries, but both indices have increased over the last four decades. There has been an increase in the occurrence of extreme 1-day precipitation events over the last hundred years, with the rate of increase accelerating in recent decades. Extremely warm maximum and minimum temperatures have shown an increasing trend over the 20th to 21st centuries and over the last four decades, while the occurrence of extremely cold maximum and minimum temperatures has decreased over these periods. The U.S. Climate Extremes Index, which integrates several extremes indices, indicates that the 1940s and 1960s were the decades of most stable (smallest occurrence of extremes) climate in the last 104 years, and that recent decades have become as unstable (variable) as, or more unstable than, the early decades of the 20th century but for different reasons.

Contents

1. Introduction

Climate variability and climate change have impacted civilization throughout history. Droughts, floods, heat waves, cold waves,

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and other extreme events touch every economic and social sector, including the foundation of civilization – agriculture. The very survival of some early civilizations came into question when the climate varied (Bryson and Murray, 1977; Fagan, 2004). In the last two centuries, scientific and technological advancement have been accompanied by a rapid increase in population and a more interconnected world. The transfer of resources and relief from unaffected regions to a region affected by a natural disaster can help lessen the impact of the disaster. But the opposite is also true: in the present global economy, a weather or climate disaster in one country can affect the economies of other countries.

Climate change has accelerated in recent decades (Sheffield and Wood, 2011). This is evident in a number of climate variables (Hartmann et al., 2013). The number of weather-related natural catastrophes has risen on all continents since 1980, most notably for North America, and this has had a dramatic impact on the insurance industry (Munich Re, 2012). Developed countries today are better able to manage the impacts of a variable climate, but in developing countries the increasing frequency and magnitude of extreme weather events pose potentially disastrous consequences for agriculture and food security (Field, 2000; Wilhite, 2005; Sheffield and Wood, 2011; Sivakumar et al., 2011a). Knowledge of how and where the climate has varied and is changing is crucial to developing successful coping strategies for agriculture and ecosystems in general.

Many aspects of climate are well represented by monthly means, and some extremes (such as drought) are analyzed using indices based on monthly data (e.g., Palmer Drought Severity Index, Standardized Precipitation Index), but information about extremes is best obtained from daily data. Consequently, an internationally agreed-upon set of daily extremes indices (ETCCDI, from Expert Team on Climate Change Detection and Indices) has been devised (Frich et al., 2002; Zhang et al., 2011; Hartmann et al., 2013). Zhang et al. (2011) suggested that multi-parameter indices, such as the Climate Extremes Index (Gleason et al., 2008) which combines daily- and monthly-based indices, might someday be added to the ETCCDI suite of extremes indices. Indices based on daily data provide insight into local conditions, but few physically-based thresholds have relevance in all parts of the world. Consequently, the daily-based indices now often focus on relative thresholds that describe features in the tails of the distributions of meteorological variables. This paper surveys trends in several climate extremes (drought, heavy precipitation/flooding, and maximum and minimum temperatures) over the last several decades to the last century across the globe, with special emphasis on those areas having adequate climate data. The importance of defining the analysis period is illustrated by a more detailed discussion of trends in extremes in the USA.

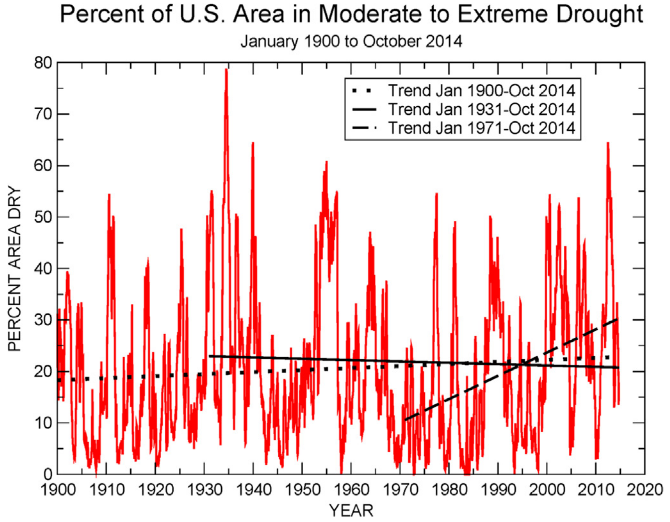

Fig. 1. The percent area of the contiguous USA (CONUS) experiencing moderate to extreme drought (Palmer Drought Severity Index (PDSI) ≤ -2.0) from January 1900 to October 2014 (red curve). The dotted line is a linear regression over the period of record (linear trend $= +0.40\%$ decade^{-1}), the solid line is for January 1931–October 2014 (-0.26% decade^{-1}), and the dashed line is for January 1971–October 2014 ($+4.49\%$ decade^{-1}). (After Fig. 4 in Peterson et al. (2013), but updated through October 2014 and based on the improved climate division dataset, nClimDiv (Vose et al., 2014).) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Characteristics of indices of weather and climate extremes

It is important that the measures of climate extremes be rigorous and clearly defined. Klein Tank et al. (2009), Zhang et al. (2011), and the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (Hartmann et al., 2013) have summarized various characteristics of climate data sets which are necessary for an adequate analysis of changes or trends in extremes. These include:

- Data availability, quality, and consistency are important as they can affect the statistics of extremes. Measurement practices (observation practices and instrumentation) should be consistent and unchanging over time.
- For statistical studies, counts of threshold exceedance (frequency, duration) and departures from high percentiles/return periods (intensity, severity, magnitude) are highly sensitive to changes in the shape and scale parameters of the statistical distribution and geographic location.
- Consistent methodologies should be used to create the datasets. Different data sets using different gridding methods (or reanalysis methodologies) and/or different input data and varying levels of quality control could affect results comparing region to region.
- The period of record (p.o.r.) should be consistent. A different p.o.r. between regions and between stations could affect spatial comparisons of trends (the importance of p.o.r. is illustrated in Figs. 1, 2, 5 and 6 later in this paper). A long p.o.r. is needed to obtain meaningful trends and statistics, and the same (or comparable) p.o.r. should be used amongst regions.
- A universal and consistent definition of extremes indices is needed, and the reference period which they are based on needs to be consistent. This fundamental characteristic is basic for not only comparison of indices between regions, but it also affects the resulting statistics. For example, for precipitation extremes, analysis and framing of questions regarding sub-daily precipitation extremes is becoming more critical; variations in the spatial pattern of trends for daily precipitation depend on event formulation and duration. The IPCC AR5 Working Group 1 identified extreme indices that have been chosen for their robust statistical properties, their applicability across climates, and their available data (Hartmann et al., 2013, Box 2.4, p. 221).
- The spatial density of surface weather stations needs to be sufficient to adequately represent the spatial variability of extremes, and the data need to be homogeneous so that false trends and variability are excluded. Hartmann et al. (2013) pointed out that non-climatic factors can affect data homogeneity and noted, as an example, that changes in flood frequency can depend on changes in river management practices.

Other issues relevant to climate extremes indices were identified by speakers at the October 2014 International Symposium on Weather and Climate Extremes, Food Security and Biodiversity in Fairfax, Virginia, USA. These include:

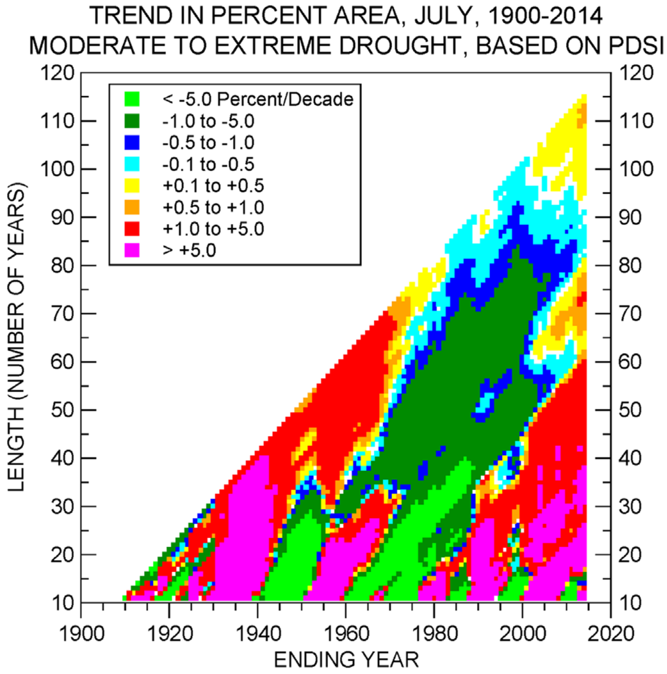

Fig. 2. Linear trend in the percent area of the CONUS experiencing moderate to extreme drought (based on the PDSI, percent area per decade) from 1900 to 2014, for record lengths of 11–115 years, plotted on the ending year of the record, for July. Warm colors indicate increasing trend (increasing drought area), cool colors indicate decreasing trend (decreasing drought area). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- Better communication is needed, both between those monitoring extremes as well as with decision-makers and other users of the extremes indices.
- Developing countries need to coordinate national observation networks across regions and continents.
- We monitor climatic and weather variables, but we also need to monitor the impacts of climate and weather events in a systematic way with data and observing systems specifically designed to measure impacts. Impacts can include, for example: crop specific metrics (yield, nutrient quality, protein content, etc.), transportation, food diversity choice, animal agriculture/aquaculture, food processing (water availability, etc.), stability of access, and socio-economic indicators (poverty, malnutrition, education, sanitation).
- Extremes indices aggregated across agricultural regions would be useful.

Many speakers at the October 2014 International Symposium on Weather and Climate Extremes, Food Security and Biodiversity discussed the need for improved data from better observation networks (more stations, denser networks, complete data, near-real time data, better international data exchange/sharing) in the developing world, and the IPCC AR5 Working Group 1 noted the inadequate data coverage in some parts of the world in their global assessment of trends in extremes (Hartmann et al., 2013). Consequently, this paper will focus on trends in the USA, where data coverage is extensive, and summarize trends in other parts of the world as presented by Hartmann et al. (2013).

3. Drought

Numerous indices and indicators have been developed over the decades to assess and monitor drought, but none of them adequately describes drought due to the complex nature of the phenomenon (WMO, 1992; AMS, 1997; Heim, 2002; Mishra and Singh, 2010; Zwiers et al., 2011; Peterson et al., 2013). In the USA and North America, the U.S. and North American Drought Monitors (USDM and NADM, respectively) have been developed to monitor drought using a “convergence of evidence” approach where numerous drought indices and indicators are examined and the drought status is determined from a subjective “best fit” or “convergence” of the indicators (Svoboda et al., 2002; Lawrimore et al., 2002; Heim and Brewer, 2010, 2012; Sivakumar et al., 2011b). This approach reflects the multiple types of drought at multiple time scales. The convergence of evidence approach is followed on a national scale in the USA, Canada, and Mexico, and the national drought depictions are integrated together into the continental NADM product. The NADM methodology is being applied globally to create a Global Drought Monitor (GDM) (Heim and Brewer, 2010, 2012; Sivakumar et al., 2011b). Unfortunately, because these products (USDM, NADM, GDM) are so new, they each have a short period of record and meaningful trends cannot be computed. Traditional drought and drought-related indices, such as the ETCCDI precipitation extremes indices and the Palmer Drought Severity Index (PDSI), have sufficiently long records to allow the computation of trends.

Fig. 1 shows the percent area of the contiguous USA (CONUS) experiencing moderate to extreme drought for January 1900–October 2014, based on the PDSI. The considerable decadal variability obviously will affect the value of linear trends, depending on the starting and ending points, as illustrated by the three trend lines in Fig. 1. Even though the recent decades have seen considerable drought, the trend for January 1931–October 2014 is negative (−0.26 percent area/decade) (T statistic −1.288) since the period begins during the high drought-area decade of the 1930s “Dust Bowl”. The trend for January 1971–October 2014 is strongly positive (+4.49) (T statistic +9.665) and reflects the increase in drought area reflected by a wet initial decade and a dry ending decade. The trend for the entire period of record, January 1900–October 2014, is also positive (+0.40) (T statistic +3.292), but only slightly. Fig. 2 illustrates the effect on linear trend of initial and ending years and length of record on a much finer temporal scale. Trends computed for short periods (10–30 years) oscillate between large positive and negative values and reflect the decadal variation in drought area as seen in the drought decades of the 1930s, 1950s, late 1980s–early 1990s, and 2000s, interspersed with comparatively wet decades. For record lengths of 30–80 years, the temporal pattern is dominated by increasing trends in the early years (reflecting the influence of the 1930s and 1950s droughts), decreasing trends in the mid-years (reflecting the influence of the wetter decades of the 1960s and 1970s), and increasing trends in the later years (reflecting the influence of the 2000s drought). Decreasing trends dominate at record lengths of 80–95 years. Century-scale trends are generally positive, indicating an increasing trend in drought area and strongly influenced by the endpoint drought decades of the 2000s. Table 1 shows the linear trend values for selected ending years and record lengths.

The spatial pattern of trends in the Palmer Hydrological Drought Index (PHDI) corresponding to the three trend periods identified in Fig. 1 is shown in Fig. 3. Much of the Great Plains, Midwest, Northeast, and Deep South, and parts of the Northwest, trend toward wetter conditions for the period of record (1900–2013) and 1931–2013, while much of the Southwest and parts of the central to northern Rockies and Southeast trend toward drier conditions. But for the 1971–2013 period, most of the country trends toward drier conditions, especially in the West, southern Plains, and Southeast, while only the northern Plains and parts of the Midwest and Northeast trend toward wetter conditions.

Daily station data from the Global Historical Climatology

Table 1
Linear trend in the percent area of the CONUS experiencing moderate to extreme drought (percent area per decade), based on the PDSI, for periods of varying length (NYRS in number of years) and ending years, for each July from 1900–2014. Blue shading indicates trends that are significant at the 0.05 level. (Due to the nature of the phenomenon, drought data are auto-correlated at the monthly time scale, and so are not independent. Nevertheless, the two-tailed *T* test indicates a *T* statistic of ± 1.96 is significant at the 0.05 level.).

	Ending Year										
NYRS	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010	2014
15	2.53	1.37	14.73	-16.27	9.79	-9.64	0.54	8.12	-8.30	5.00	-1.77
20	-2.64	3.35	12.01	-15.82	11.88	-14.13	-5.95	8.32	3.46	8.88	8.57
25		1.65	10.30	-6.42	2.30	-3.04	-5.36	5.50	0.10	1.96	8.34
30		-0.42	9.30	-2.71	-1.88	1.51	-8.99	0.90	2.18	5.44	4.72
35			7.03	-0.30	0.02	-1.19	-4.28	-0.42	2.11	3.41	5.18
40			4.91	1.30	0.89	-2.88	-1.39	-3.68	0.10	4.01	4.60
45				1.35	1.77	-1.52	-2.53	-1.80	-0.57	3.69	4.61
50				0.93	2.48	-0.68	-3.43	-0.36	-2.70	2.14	4.12
55					2.31	0.18	-2.43	-1.33	-1.59	1.38	2.63
60					1.89	0.92	-1.71	-2.14	-0.61	-0.40	1.58
65						1.02	-0.95	-1.62	-1.28	0.09	0.42
70						0.88	-0.25	-1.19	-1.89	0.61	0.90
75							-0.05	-0.68	-1.53	-0.04	0.99
80							-0.03	-0.18	-1.22	-0.65	0.44
85								-0.03	-0.81	-0.50	-0.33
90								-0.02	-0.40	-0.36	-0.07
95									-0.26	-0.11	0.13
100									-0.23	0.16	0.30
105										0.22	0.29
110										0.21	0.53
115											0.41

Network (GHCN-Daily) (Menne et al., 2012) has been used to compute the percent area of the CONUS having above-normal number of days with and days without precipitation, where above normal conditions are defined as those falling in the upper tenth percentile of the local period of record. The annual percent area of above-normal number of days with (without) precipitation has increased (decreased) at a rate of 10.8 (−13.0) percent century^{-1} over the 1910–2013 period (Fig. 4) and 10.9 (−8.2) percent century^{-1} over the 1931–2013 period. For the period 1971–2013, both the days with and without precipitation indicators have increased at a rate of 6.8 and 8.8 percent century^{-1}, respectively.

As noted in the IPCC Fifth Assessment Report, numerous studies using various drought indices have found differing trends in global droughts and/or dryness since the middle of the 20th century, with decadal variability dominating longer-term trends (Hartmann et al., 2013). The annual maximum number of consecutive dry days (an ETCCDI extremes index, not a drought index), which is defined as the maximum number of consecutive days with precipitation <1 mm (Box 2.4, Table 1, in Hartmann et al., 2013, p. 221), has declined since the 1950s in more regions than it has increased (Fig. 2.33c in Hartmann et al., 2013, p. 215). Regional trends are evident in the global studies cited in the AR5, including increasing dryness or drought in East Asia, the Mediterranean, and West Africa, and decreasing dryness or drought in central North America and northwest Australia (Hartmann et al., 2013, p. 215).

4. Heavy precipitation, flooding

The PDSI was designed to show excessive precipitation as well as drought. Fig. 5 shows the percent area of the CONUS experiencing moderate to extreme wet spell conditions, based on the PDSI. The trend for January 1931–October 2014 is positive (+1.37 percent area/decade) (T statistic +7.743) and for January 1971–October 2014 is negative (−2.14) (T statistic −4.471), both the opposite of their drought counterparts (Fig. 1). But the trend for the entire period is positive (+0.27) (T statistic +2.426), which is the same sign as the drought counterpart, suggesting that the climate is trending toward both extremes (wetter and drier) over the century scale. As with drought in Fig. 2, Fig. 6 illustrates the effect of initial and ending years and length of record on the linear trend of wet spell area. Trends computed for short periods (10–30 years) oscillate between large positive and negative values and reflect the decadal variation in wet spell area. For record lengths of 30–50 years, the temporal pattern is dominated by decreasing trends in the early years (reflecting the influence of the 1930s and 1950s droughts, thus absence of wet spell area), increasing trends in the mid-years, and decreasing trends in the last decade and a half. Trends at 80+ years are generally positive, indicating an increasing trend in wet spell area and reflecting the high frequency of unusually wet conditions during the last 40 years. The unusual wetness of the last 40 years is also seen in the notable shift from decreasing to increasing trends in the early 1970s across the length spectrum.

The percent area of the CONUS experiencing a much greater than normal proportion of annual precipitation derived from

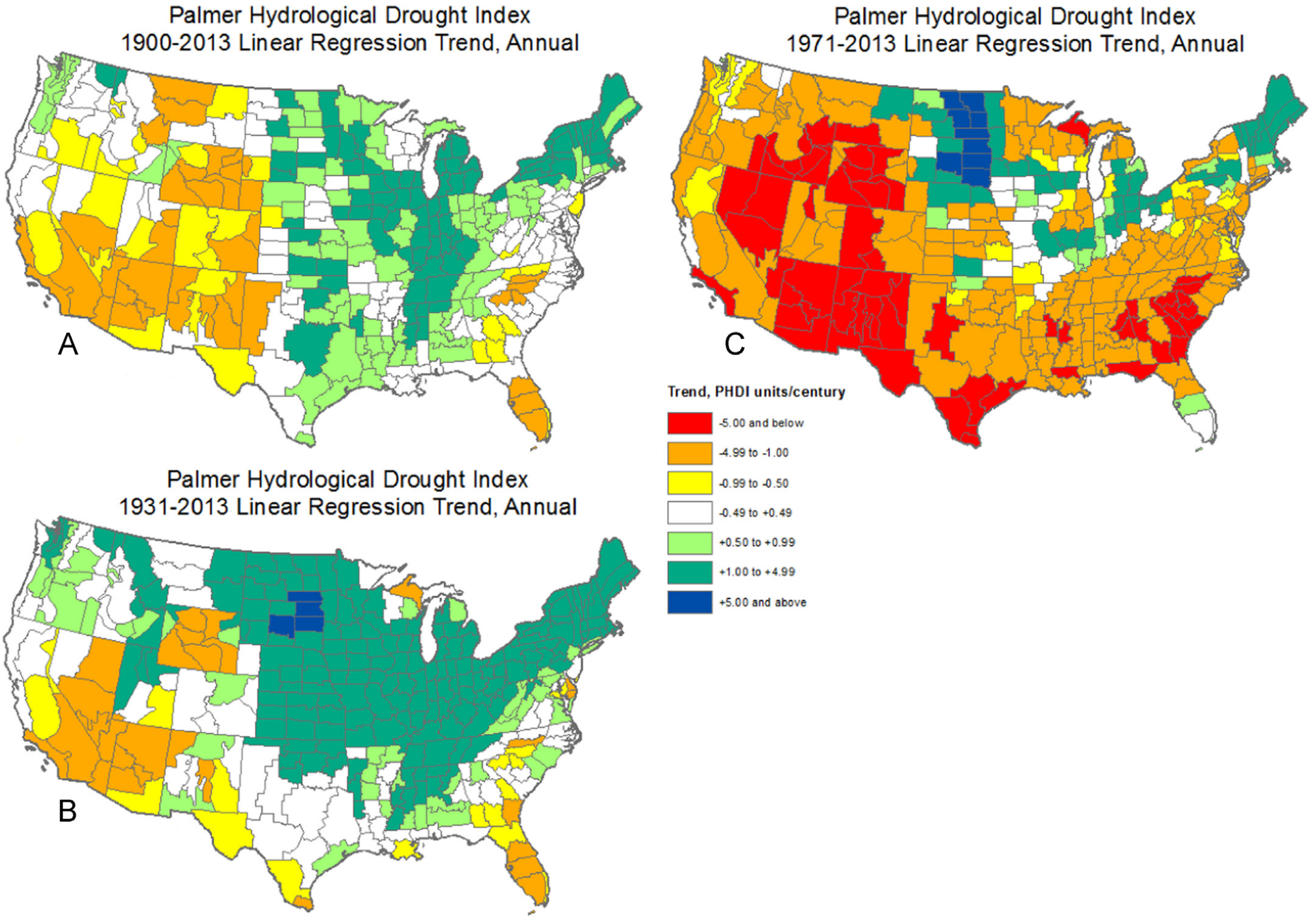

Fig. 3. Linear trend in annual Palmer Hydrological Drought Index (PHDI units century^{-1}) across the CONUS for three periods: (A) 1900–2013, (B) 1931–2013, and (C) 1971–2013. Warm colors are increasing dryness (decreasing wetness), cool colors are decreasing dryness (increasing wetness). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

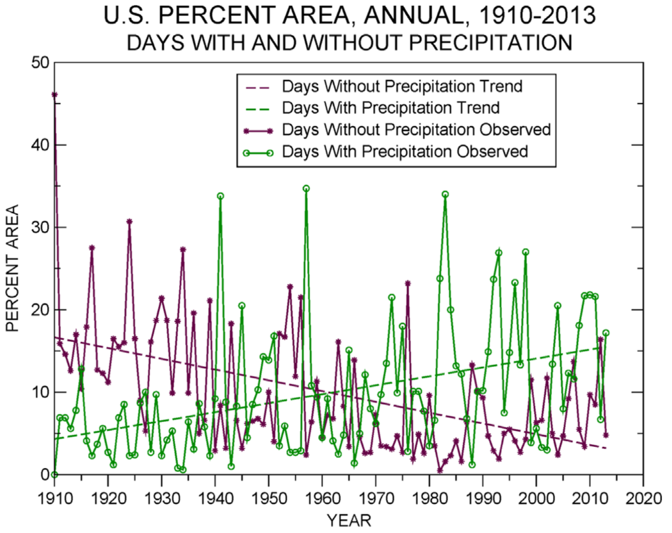

Fig. 4. Percent area of the CONUS with a much greater than normal annual number of days with (green curve) and without (brown curve) precipitation, 1910–2013, where above normal conditions are defined as those falling in the upper tenth percentile of the local period of record. Based on daily station precipitation data from the Global Historical Climatology Network (GHCN-Daily) dataset (Menne et al., 2012). The days with (days without) precipitation percent area data have a linear trend of +10.8 (−13.0) percent century^{-1} over the period of record (dashed lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

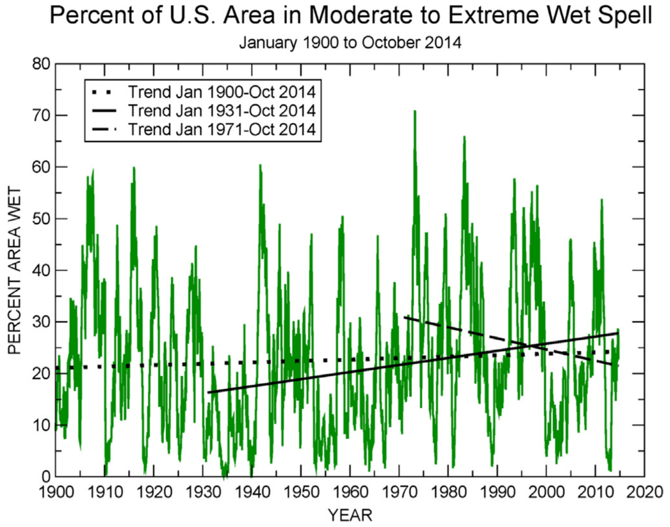

Fig. 5. As in Fig. 1, except for moderate to extreme wet spell conditions [PDSI $\geq +2.0$] from January 1900 to October 2014 (green curve). The dotted line is a linear regression over the period of record (linear trend = +0.27% decade^{-1}), the solid line is for January 1931–October 2014 (+1.37% decade^{-1}), and the dashed line is for January 1971–October 2014 (−2.14% decade^{-1}). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

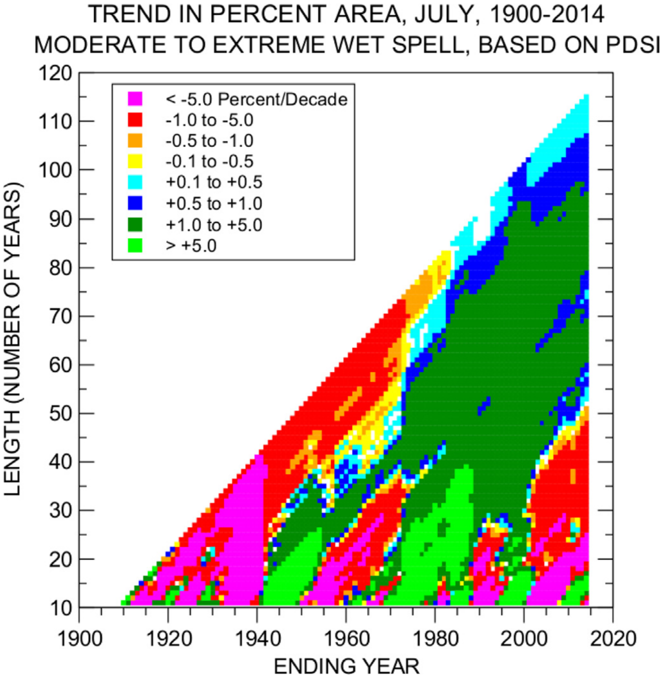

Fig. 6. As in Fig. 2, except for percent area of the CONUS experiencing moderate to extreme wet spell conditions. Warm colors indicate decreasing trend (decreasing wet spell area), cool colors indicate increasing trend (increasing wet spell area). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

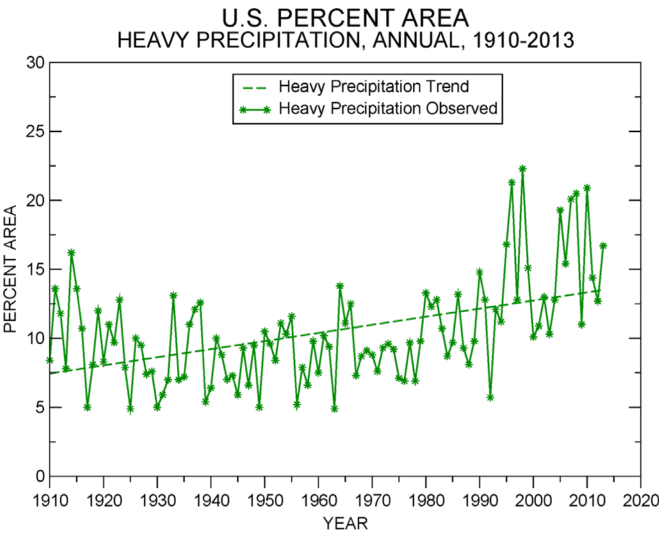

Fig. 7. Percent area of the CONUS with a much greater than normal proportion of precipitation derived from extreme (highest tenth percentile) 1-day precipitation events, 1910-2013. Based on daily station precipitation data from the GHCN-Daily dataset (Menne et al., 2012). The extreme precipitation percent area data have a linear trend of +5.9 percent century^{-1} over the period of record (dashed line).

extreme (highest tenth percentile) 1-day precipitation events has increased over the period of record at a rate of 5.9 percent century^{-1} (Fig. 7). The rate of increase has accelerated during more recent periods (9.9 percent century^{-1} for 1931–2013 and 21.2 percent century^{-1} for 1971–2013). Regionally, the increase is greatest in the Northeast, Midwest, and Southeast; smallest in the Southwest; and negative (decreasing trend) over the Hawaiian Islands (Figs. 2.17 and 2.18, Melillo et al., 2014, pp. 36–37).

Global assessments of the trend in heavy precipitation events are based on several indices. Trends, over the period 1951–2010, in the annual amount of precipitation derived from days with precipitation amounts >95th percentile vary across the continents but are positive over more areas than they are negative (Hartmann et al., 2013, p. 213; also Fig. 2.33a, p. 215). Similar results are found in the sign and spatial pattern of trends in the Simple Daily Intensity Index, which is defined as the ratio of annual total precipitation to the number of wet days (precipitation ≥1 mm) (Hartmann et al., 2013, p. 213; also Fig. 2.33b, p. 215). The trends are also dependent on season. Europe and central North America show consistent trends toward heavier precipitation events (Hartmann et al., 2013, p. 214).

Heavy daily rainfall may cause local flooding, but widespread flooding of large rivers requires more extensive rainfall or snow melt. Hydrologic data in local areas can be affected by land-use and river management changes (Hartmann et al., 2013; Melillo et al., 2014), which further complicates analysis of flood data. Annual flood magnitude has increased in the USA Midwest and Northeast, and decreased in the Southwest, over the 1920s-2008 period (Fig. 2.21, Melillo et al., 2014, p. 40). It is difficult to make conclusions regarding the sign of trend in the magnitude and/or frequency of floods on a global scale, although the most evident flood trends appear to be in northern high latitudes, where observed warming trends have been largest, and there is evidence of earlier spring flow in snow-dominated regions (Hartmann et al., 2013, p. 214).

5. Maximum temperature

Daily station data from the U.S. Historical Climatology Network (USHCN) (Karl et al., 1990) has been used to compute the percent area of the CONUS having much above normal (much below normal) maximum and minimum temperatures, where much above (below) normal temperatures are defined as those falling in the upper (lower) tenth percentile of the local period of record. The annual percent area of much above (below) normal maximum temperatures has increased (decreased) at a rate of 9.8 (−10.7) percent century^{-1} over the 1910–2013 period (Fig. 8), 9.4 (−1.6) percent century^{-1} over the 1931–2013 period, and 71.7 (−33.4) percent century^{-1} over the 1971–2013 period. The linear trend is

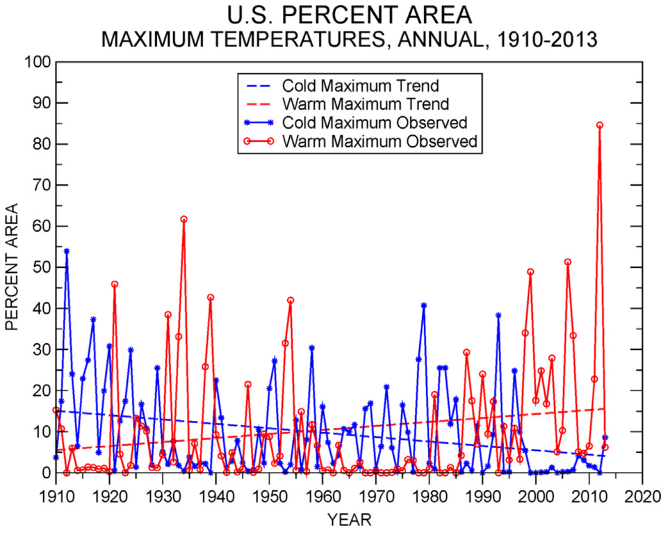

Fig. 8. Percent area of the CONUS with annual maximum temperatures falling in the upper tenth percentile (red curve) and lower tenth percentile (blue curve), 1910–2013. Based on daily station temperature data from the U.S. Historical Climatology Network (USHCN) dataset (Karl et al., 1990). The warm (cold) maximum temperature percent area data have a linear trend of +9.8 (−10.7) percent century^{-1} over the period of record (dashed lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

highly influenced by the beginning and end points of the period analyzed, as can be seen in Fig. 8. The high frequency of unusually warm maximum temperatures during the drought decades of the 1930s and 1950s, the low frequency during the 1960s and 1970s, and high frequency during the 1980s–2000s would support a two-phase trend, i.e., decreasing trend of -7.5 percent century^{-1} over the 1910–1970 period and increasing trend of $+71.7$ percent century^{-1} over the 1971-2013 period.

The IPCC Fifth Assessment Report shows a similar trend globally toward fewer cold days (lower tenth percentile) and more warm days (upper tenth percentile) for the period 1951–2010 (Figs. 2.32b and 2.32d, respectively, Hartmann et al., 2013, p. 210). The AR5 summary shows that, regionally, the trend toward fewer cold days and more warm days dominates most of the world, except for portions of South America and southeast North America (Hartmann et al., 2013, pp. 209, 212). There has also been an increase in the frequency of heat waves since the middle of the 20th century in Europe and Australia and across much of Asia where sufficient data exist (Hartmann et al., p. 212).

6. Minimum temperature

The annual percent area of the CONUS experiencing much above (below) normal minimum temperatures has increased (decreased) at a rate of 17.9 (-17.4) percent century^{-1} over the 1910–2013 period (Fig. 9), 25.6 (-10.0) percent century^{-1} over the 1931–2013 period, and 74.0 (-33.8) percent century^{-1} over the 1971–2013 period. The warming trend in minimum temperatures has resulted in an increase in the frost-free season, which is defined as the period between the last occurrence of 0 °C in the spring and the first occurrence of 0 °C in the fall. The increase in frost-free season has occurred across the CONUS, with the greatest increases occurring in the Southwest and Northwest (Fig. 2.10, Melillo et al., 2014, p. 31).

As with maximum temperature, the AR5 summary shows a similar trend globally for minimum temperature. The period 1951–2010 has experienced fewer cold nights (lower tenth percentile) and more warm nights (upper tenth percentile), with these trends occurring almost everywhere on all continents where data were sufficient for analysis (Figs. 2.32a and 2.32c, Hartmann et al., 2013, p. 210). The rate of increase in warm minimum temperatures appears to be greater than the rate of increase in warm maximum temperatures, with an accompanying decline in diurnal temperature range (Hartmann et al., 2013, p. 209).

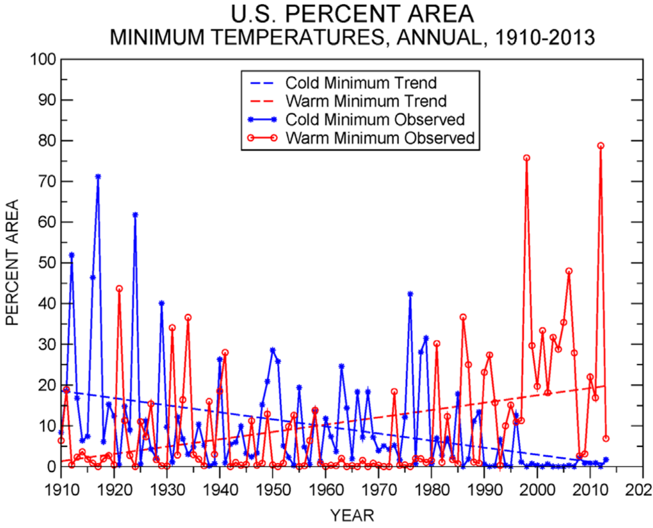

Fig. 9. As in Fig. 8, except for annual minimum temperatures. The warm (cold) minimum temperature percent area data have a linear trend of $+17.9$ (-17.4) percent century^{-1} over the period of record. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

7. Integrating multiple measures of extremes into one index

As summarized by Hartmann et al. (2013), Gallant et al. (2014), and others, coherent trends in climate extremes over large areas have been identified. By integrating multiple measures of extremes into one index, such as the Climate Extremes Index (CEI), information from complex spatiotemporal fields can be distilled into a simple form that informs the user whether an area is becoming more or less extreme and, if desired, identifies the sign of these changes (Gallant et al., 2014). Gallant et al. (2014) further note that the usefulness of the CEI lies in its ability to examine extremes that are relevant for socioeconomic and physical impacts and that are from widely and readily available data that can be compared worldwide. These features are crucial for examining large-scale and coherent changes across the globe and make the indices relevant, calculable, and comparable for multiple regions of any size (e.g., state or country scale to global scale).

The CEI integrates several components that assess changes in temperature and moisture-related extremes and returns a percentage value representing the fractional area of a region affected. In the USA (USCEI), the percentage of the CONUS experiencing extremes at both ends of the distribution is summed. The USCEI aggregates the climate extremes indicators discussed in Sections 3–6 above, i.e., the percentage of the CONUS: with maximum and minimum temperatures much above (upper tenth percentile) and much below (lower tenth percentile) normal; in severe to extreme drought (PDSI $\leq$ bottom tenth percentile) or wet spell (PDSI $\geq$ upper tenth percentile); with a much greater than normal proportion of precipitation derived from extreme (equivalent to the highest tenth percentile) 1-day precipitation events; and with a much greater than normal number of days with and without precipitation (Karl et al., 1996; Gleason et al., 2008). (A different threshold for PDSI is used in the revised USCEI than was discussed in Section 3 (Gleason et al., 2008). A sixth indicator (the sum of squares of U.S. landfalling tropical storm and hurricane wind velocities scaled to the mean of the first five indicators) is included in an experimental version of the USCEI (Gleason et al., 2008), but this experimental indicator is not included in the present discussion.) Gallant and Karoly (2010) modified this approach in the modified CEI (mCEI) and daily modified CEI (dmCEI) and instead subtracted the extremes from one tail in a distribution from those from the opposite tail instead of adding them (Gallant et al., 2014).

The annual USCEI has an increasing trend over the 1910–2013 period of record of 3.5 percent century^{-1}, but this does not accurately reflect the changes that have occurred over this time. The data show a decreasing trend of -17.0 percent century^{-1} during the first part of the record and an increasing trend of 34.1 percent century^{-1} during the last part of the record, with the inflection point occurring in 1969–70 (Fig. 10). The decreasing trend during the first part of the 20th century reflects the decreasing trend in certain components (cold maximum and minimum temperatures, days without precipitation), while the increasing trend during the last part of the 20th century and first decades of the 21st century reflects the increasing trend of other components (warm maximum and minimum temperatures, heavy precipitation events, days with precipitation), and is due to the addition of the tails of the extremes. The USCEI suggests that, based on the integration of these extremes indicators, the 1940s and 1960s were the decades of most stable (least extreme) climate in the last 104 years. Also of interest is the fact that the rate of increase of the USCEI during 1970–2013 is twice the magnitude of its rate of decrease during

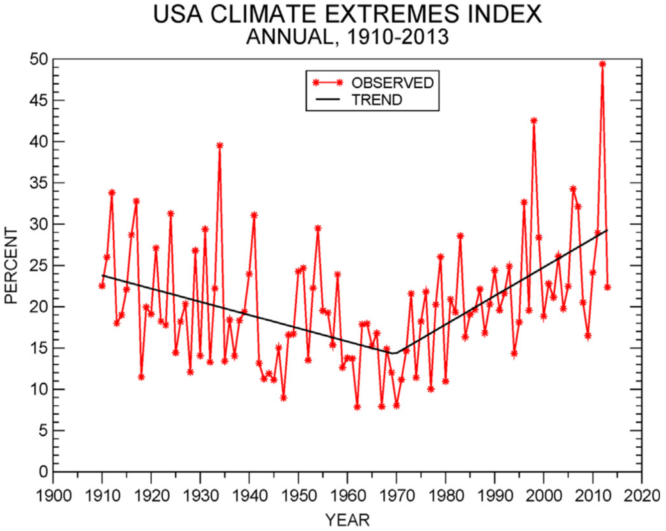

Fig. 10. Annual Climate Extremes Index (USCEI) (Gleason et al., 2008) for the CONUS, 1910–2013 (red curve). The solid black line is a two-phase linear trend which is decreasing at a rate of −17.0 percent century^{-1} from 1910–1969 and increasing at a rate of +34.1 percent century^{-1} from 1970–2013. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1910–1969. Gleason et al. (2008) related the change in trend in the late 1960s-early 1970s to research indicating that a change in atmospheric circulation occurred at this time (Namias, 1978; Trenberth, 1990; Ebbesmeyer et al., 1991; Graham, 1994; Trenberth and Hurrell, 1994). Hartmann et al. (2013) noted that, since the 1970s, large-scale sea level pressure patterns have changed over the tropical Atlantic (decreased) and Pacific and South Atlantic (increased), with a widening of the tropical belt, and a poleward shift in circulation features (such as storm tracks and jet streams) has occurred.

Gallant et al. (2014) computed the mCEI and dmCEI for three near-continental-size landmasses of the CONUS, Europe, and Australia over the period 1950–2012 and determined that both indices in all three regions increased by at least 2.6 percent decade^{-1}. These changes resulted from increasing areas of warm extremes; decreasing areas of cool, maximum, and minimum annual and daily temperature extremes; and increasing areas where the proportion of annual total precipitation falls on heavy-rain days. They determined that there were no statistically significant trends toward more widespread, annual-scale drought or moisture surplus in any region. Their analysis found strong covariations between annual- and daily-scale extremes in all regions, indicating the dependence of annual extremes on the frequency of daily-scale extremes.

8. Summary and conclusions

This review article has noted many parts of the world which have experienced increasing trends in climate and weather extremes during the last 50–100 years. These trends have been identified in numerous regional and global analyses which have been summarized by the Intergovernmental Panel on Climate Change in a series of reports, with the latest (Fifth Assessment Report) released in 2013. A set of daily (ETCCDI) and monthly extremes indices has been internationally agreed upon to measure these changes. Care must be taken in the preparation and analysis of data sets, and in the definition of extremes indices, to ensure an accurate representation of changes in climate and to enable global assessments.

Significant trends in maximum and minimum temperature extremes have been observed in many parts of the world. There is a trend globally toward fewer cold days and nights and more warm days and nights. The annual amount of precipitation derived from days with heavy precipitation events is increasing over Europe and central North America; trends in this index vary over the other continents but are positive over more areas than they are negative. Decadal variability dominates longer-term trends in drought and dryness extremes, although regional trends are evident, including increasing dryness or drought in East Asia, the Mediterranean, and West Africa, and decreasing dryness or drought in central North America and northwest Australia.

Several of the climate extremes indicators have been merged to create an integrated Climate Extremes Index. The USCEI annual time series exhibits a two-phase trend over the USA, decreasing to the late 1960s-early 1970s and increasing thereafter. This reflects the decreasing trend of the cold-extreme-based indicators and the increasing trend of the warm-extreme-based and extreme precipitation indicators. The trend inflection point of 1969–70, seen in the USCEI data, is quite evident in the USA PDSI-based wet spell area data. Similar increasing trends in the CEI are evident over the last 60 years in Europe and Australia.

The trends in these climate extremes pose a serious risk to food security in many parts of the world. Negative impacts of these climate trends on crop and terrestrial food production are more common than positive impacts (Porter et al., 2014): there have been several periods of rapid food and cereal price increases following the occurrence of climate extremes; several crops in many regions are negatively affected by hot temperature extremes (maximum temperatures ≥30 °C); and crop production is expected to be consistently and negatively affected by climate change in low-latitude countries.

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