A Revised U.S. Climate Extremes Index

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ABSTRACT

A revised framework is presented that quantifies observed changes in the climate of the contiguous United States through analysis of a revised version of the U.S. Climate Extremes Index (CEI). The CEI is based on a set of climate extremes indicators that measure the fraction of the area of the United States experiencing extremes in monthly mean surface temperature, daily precipitation, and drought (or moisture surplus). In the revised CEI, auxiliary station data, including recently digitized pre-1948 data, are incorporated to extend it further back in time and to improve spatial coverage. The revised CEI is updated for the period from 1910 to the present in near–real time and is calculated for eight separate seasons, or periods.

Results for the annual revised CEI are similar to those from the original CEI. Observations over the past decade continue to support the finding that the area experiencing much above-normal maximum and minimum temperatures in recent years has been on the rise, with infrequent occurrence of much below-normal mean maximum and minimum temperatures. Conversely, extremes in much below-normal mean maximum and minimum temperatures indicate a decline from about 1910 to 1930. An increasing trend in the area experiencing much above-normal proportion of heavy daily precipitation is observed from about 1950 to the present. A period with a much greater-than-normal number of days without precipitation is also noted from about 1910 to the mid-1930s. Warm extremes in mean maximum and minimum temperature observed during the summer and warm seasons show a more pronounced increasing trend since the mid-1970s. Results from the winter season show large variability in extremes and little evidence of a trend. The cold season CEI indicates an increase in extremes since the early 1970s yet has large multidecadal variability.

1. Introduction

The U.S. Climate Extremes Index (CEI) was first introduced in an effort to quantify observed changes in climate within the contiguous United States (CONUS) (Karl et al. 1996). At that time, the scientific community had a reasonable understanding of changes in mean conditions across the United States and the globe, which are well documented, yet there remained a general lack of observational data on extremes. In an effort to assist policymakers and inform the general public regarding our understanding of changes in global climate, The Intergovernmental Panel on Climate Change (IPCC) published its initial findings in the First Assessment Report (FAR) in 1990 and subsequently updated and revised these findings as new data and information became available in reports issued in the Second Assessment Report (SAR; Houghton et al. 1995), the Third Assessment Report (TAR; Houghton et al. 2001), and the Fourth Assessment Report (AR4; Solomon et al. 2007). In the FAR and SAR, evidence was presented that identified climate change signals primarily through trend analysis of linear increases/decreases in mean conditions. With the TAR and AR4, some analysis of changes and variability in observed extremes were made, mostly on continental and global scales.

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The CEI was developed as a "first-glance" monitoring and communications tool to help U.S. citizens and policymakers identify possible trends or long-term variations in a variety of climate extremes indicators including those found in observed surface temperature and precipitation across the contiguous United States. It was not designed to identify causes and origins of variability and change in climate and weather extremes. The CEI values provide information on the percentage of the contiguous United States that experienced extreme conditions during any given year or period. Individual indicators that comprise the overall index provide details regarding the spatial characteristics of the various parameters over time. [For additional background information regarding the original CEI, please see Karl et al. (1996).]

The CEI is composed of five indicators, or steps, that illustrate possible extremes in monthly mean maximum and minimum temperature, extreme 1-day precipitation, days with/without precipitation, and the Palmer Drought Severity Index (PDSI) on an annual or seasonal basis (see the appendix for a detailed explanation of how each indicator is calculated). Extremes for each indicator are defined as occurrences that are much above/below normal (outside the 90th/10th percentile value) over the period of record. The value of the indicator for each variable is the fraction of the area of the CONUS experiencing extreme conditions in that variable. The addition of recently digitized pre-1948 daily precipitation data helps to fill in data gaps from this period in the early twentieth century and to make more consistent spatial comparisons across the country. In addition, our ability to monitor various climate parameters in near–real time has also improved as electronic data ingest practices have become more common and advances in computing technology, which allows timely processing of large amounts of data, thus allowing the index to be updated on an operational basis.

In this article, we focus on presenting the changes and additions that have been made to the original CEI indicators. A more technical discussion of the individual indicators in the revised CEI is also presented to provide additional details that were absent from the original paper. Also included is a discussion of how current extremes compare with historical extremes and comparisons between components of the new and original CEI since the index was first published over 10 years ago. The revised CEI is now calculated operationally for eight separate seasons or periods: spring (March–May), summer (June–August), autumn (September–November), winter (December–February), annual (January–December), warm (April–September), cold (October–March), and year to date (YTD). In addition, some modifications were made to the methodologies in the original indicators of the CEI and additional data have been incorporated including daily precipitation data from a National Climatic Data Center (NCDC) dataset containing pre-1948 data.

2. Data used

The original CEI utilized over 600 continuous, well-distributed observing sites across the United States that provide measures of monthly mean maximum and minimum temperature. These data were a subset of the U.S. Historical Climatology Network (HCN; Karl et al. 1990). The revised CEI considers for temperature the full HCN database (1221 stations), but utilizes only those stations for which monthly temperature data are at least 90% complete for the period of record and within a given period (e.g., annual or seasonal). The period of record for each station begins in 1910 and continues to the present. A 90% completeness threshold was selected so as to maximize spatial coverage and minimize artificial trends occurring at the beginning of the century owing to reduced station availability. As shown in Fig. 1a, this criterion reduces the number of usable stations to just over 1100, which translates to approximately 600 $1° \times 1°$ grid cells. HCN data have been adjusted to remove several nonclimatic influences: a priori adjustments including observing time biases (Karl et al. 1986), urban heat island effects (Karl et al. 1988), and the bias caused by the introduction of the maximum–minimum thermistor and its instrument shelter (Quayle et al. 1991); a posteriori adjustments included station and instrument changes (Karl and Williams 1987).

Extremes in daily precipitation and the number of rain days were originally determined from a subset of 131 HCN stations and supplemented by non-HCN stations in the West where coverage was sparse. The revised CEI utilizes the Cooperative Summary of the Day (TD3200) and a more recently digitized pre-1948 dataset (TD3206)[1] daily precipitation stations, which satisfy the 90% completeness threshold for both period of record and within a given seasonal period. Figure 1b illustrates that over 1300 daily precipitation stations meet these criteria, which cover more than 600 $1° \times 1°$

[1] The TD3200 dataset contains various parameters consisting of daily maximum and minimum temperatures, snowfall, and 24-h precipitation totals that are initially obtained from state universities, state cooperatives, and the National Weather Service. The TD3206 dataset is a compilation of daily digitized manuscript records that are not included in TD3200. These records generally date back to the late 1890s and end around 1948.

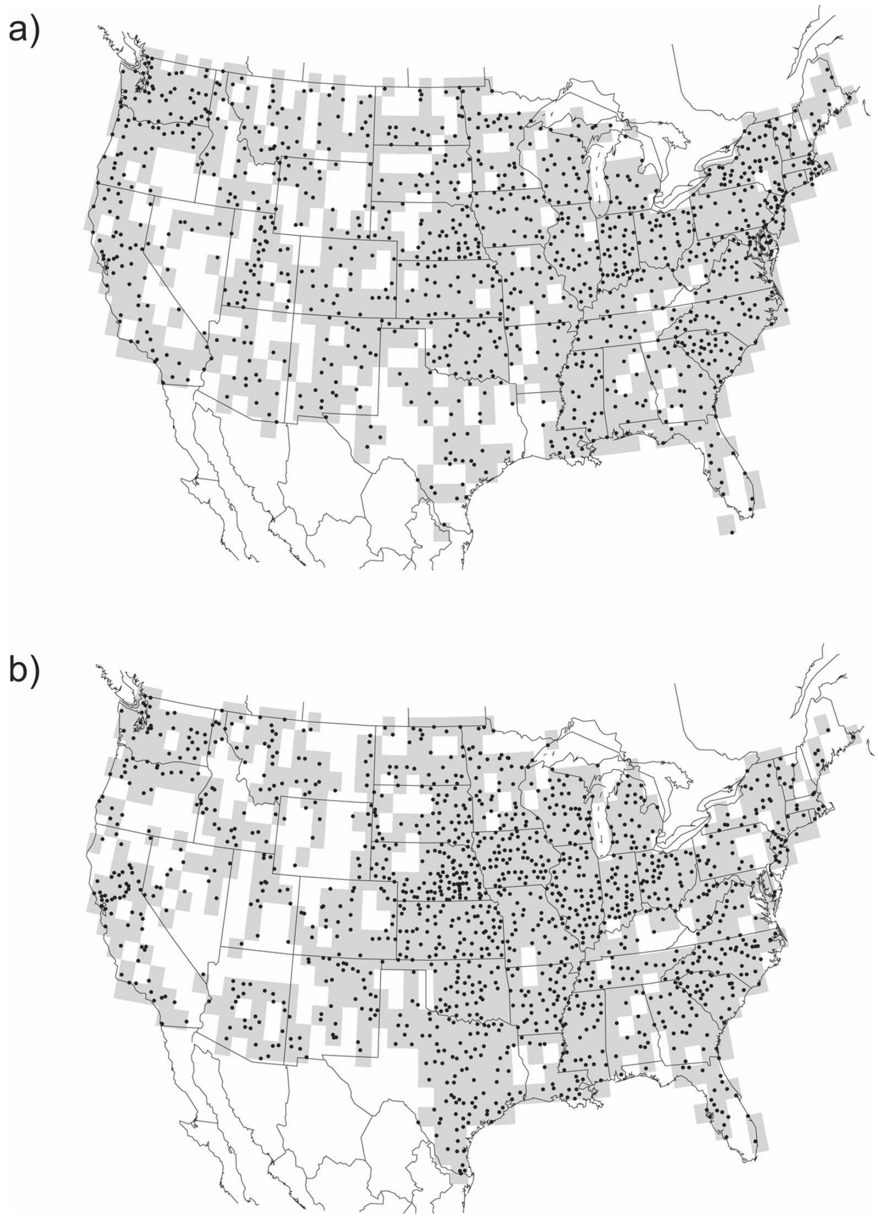

FIG. 1. (a) Monthly U.S. HCN temperature stations and (b) daily summary of the day (TD3200 and TD3206) precipitation stations used with the revised CEI. Stations included are at least 90% complete for the annual period from 1910 to 2006.

grid cells. One precipitation station per grid cell is utilized since averaging daily precipitation values within the same grid cell reduces the value of extreme events, especially in convective scenarios. When more than one station within a grid cell satisfied the inclusion criteria, the station with the longest and most complete period of record was selected to represent that grid cell. As with the temperature indicators, the percentage of the U.S. area that is extreme is determined by the grid cells that contain station data. The same area-weighting scheme is used to achieve a national area percentage for the extreme precipitation indicators. The definition of days with rain in the fifth indicator is days with at least a trace of precipitation (greater than 0.00 in. but less than 0.01 in.).

The analysis of prolonged periods of abnormally dry or wet conditions is made with the PDSI. The National Climatic Data Center climate division monthly precipitation and temperature database is used to calculate the historical PDSI values (Karl 1986), as the PDSI is cal-

Table 1. The original and revised definitions for the individual indicators that comprise the CEI. Much above/below-normal or extreme conditions are defined as those falling in the upper/lower 10th percentile of the local period of record. (See the appendix for additional details.)

Step	Original CEI	Revised CEI
1	The sum of (i) percentage of the United States with maximum temperatures much below normal and (ii) percentage of the United States with maximum temperatures much above normal.	Same.
2	The sum of (i) percentage of the United States with minimum temperatures much below normal and (ii) percentage of the United States with minimum temperatures much above normal.	Same.
3	The sum of (i) percentage of the United States in severe drought (equivalent to the lowest 10th percentile) based on the PDSI and (ii) percentage of the United States with severe moisture surplus (equivalent to the highest 10th percentile) based on the PDSI.	Same, but does not assume ±3 for threshold value. New indicator uses highest/lowest 10th percentile threshold values as determined by data from each climate division.
4	Twice the value of the percentage of the United States with a much greater-than-normal proportion of precipitation derived from extreme (more than 2 inches or 50.8 mm) 1-day precipitation events.	Same, but extreme 1-day precipitation event threshold value determined by the distribution of the data within each 1°× 1° grid cell rather than a fixed threshold- (equivalent to the highest 10th percentile).
5	The sum of (i) percentage of the United States with a much greater-than-normal number of days with precipitation and (ii) percentage of the United States with a much greater-than-normal number of days without precipitation.	Same.

culated at the divisional scale. PDSI values are categorized in increasing order of intensity as near normal, mild to moderate, severe, or extreme for both drought and wetness. Since climate division averages are used instead of grid cells, coverage for this indicator is 100% across the CONUS.

The revised CEI supplements historical data with near-real-time data for calculation and routine update of an operational CEI. Time delays waiting for near-real-time data to undergo full quality control reviews require that preliminary CEI values be replaced with updated values once the preliminary data are finalized. This typically occurs within four to six months after the end of the data month and results in small changes to the seasonal CEIs. In addition, other small changes in CEI values occur as additional station reports not collected in near-real time are incorporated into the final datasets.

3. Modifications and analysis

The components of the original CEI are presented in the left column of Table 1. Each indicator is based on the percentage area of the United States that experienced extreme conditions. Extreme criteria are defined as the 10th and 90th percentile values over the period of record for most indicators. Extremes in 1-day precipitation are evaluated only at the 90th percentile, and the resulting extreme value is subsequently doubled when results are combined with the other indicators. As each indicator now has the same expected average extreme value (approximately 20%) and the same scale, they can easily be averaged together to yield the CEI. It is necessary for the threshold values at the top/bottom 10% of occurrence to be recomputed as new data become available since, by definition, the intent is to capture only those events that meet or exceed this threshold. Identifying a target or expected value in extremes for each season or period helps to indicate periods of elevated/diminished extremes throughout the historical record.

The original CEI was intended to be a baseline index that could be further developed as additional data became available, as new climate extreme indicator datasets became more easily available, and as computer technology advanced to better handle more sophisticated processing techniques. Over the past few years, several methodological modifications were made to the original index. In addition, datasets used to calculate the index were expanded.

a. *Additions to the original CEI—Increased data availability*

The revised CEI utilizes additional data that were not available during development of the original index. The TD3206 database consists of daily records from the pre-1948 period. These data were keyed from paper and film records and then made available digitally by the National Climatic Data Center through its Climate Database Modernization Program (Ross 2004). In an effort to improve spatial resolution across the United States, the revised CEI includes the entire U.S. HCN monthly temperature dataset as well as all of the TD3200 and TD3206 data for daily precipitation data. Records for each variable are only used if they are 90% complete within an analysis period and for the period of record. As a result, all available stations are not included in the index and the number of stations used from month to month is variable.

In the original CEI, the fourth and fifth indicators utilized a subset of daily precipitation stations from the HCN network plus additional stations in the West where coverage was sparse. No interpolation scheme was implemented to fill in missing areas, so it is likely that only between 100 and 150 1° × 1° grid cells were used, which is equivalent to approximately 12%–18% coverage across the CONUS. The revised indicators include hundreds more stations. As a result, multiple stations are often located within the same 1° × 1° grid cell. Of those precipitation stations considered suitable (at least 90% completeness within a period/season as well as for the period of record), over 600 grid cells are utilized, which covers more than 70% of the CONUS. For monthly mean maximum and minimum temperatures, approximately 600 grid cells satisfy these criteria. This is similar to the temperature coverage provided in the original analysis.

Since a limited number of available stations were being utilized in the CEI precipitation analyses and the possibility exists that the density of these stations may not adequately represent the overall precipitation pattern across the continental United States, an investigation was performed to evaluate the possibility of reducing the grid box size for the two precipitation indicators to 0.5° × 0.5° and increasing the spatial resolution by as much as a factor of 4. In doing so, more data would be available for use; theoretically, the extreme results have the potential to be a more accurate and complete representation of conditions across the country.

By increasing the spatial resolution, this proposed method would utilize over 1100 stations with 90% completeness for both period of record and within a given seasonal period. Comparing results from the 1° × 1° and 0.5° × 0.5° resolutions in the fourth indicator (heavy 1-day precipitation), we see many similarities (Fig. 2). In fact, many of the annual extreme values throughout the record are nearly identical. Results from the 0.5° × 0.5° resolution plot appear less extreme, yet the 5-yr moving average values from both plots have many similar characteristics. Year-to-year differences between the two plots indicate slightly larger extreme values at the 1° × 1° resolution, with the most notable differences in extremes between the two resolutions occurring from the 1970s through 2006. It was decided that, as the comparison results are actually quite similar, the minimal benefit gained by increasing the spatial resolution is, at present, outweighed by the increase in processing time at the 0.5° × 0.5° resolution.

b. Changes to the original CEI

1) Extreme threshold criteria redefined

Several modifications have been made to the original indicators that are comprised in the CEI. One such modification relates to how extreme threshold criteria are defined. This was based on the determination that extreme threshold criteria for two of the five original indicators in the CEI were not true representations of the upper and lower 10th percentile of each distribution.

Extremes in daily precipitation, the fourth indicator in the CEI, were originally based on a fixed 50.8-mm (2 inch) threshold for the extreme criteria across the entire CONUS. An analysis was performed during late 2004 that sorted all the daily precipitation values over the entire period of record for each grid cell and determined the value at the 90th percentile position. Each of these threshold values was plotted in the appropriate grid cell position on a map to determine if a fixed threshold across the CONUS was reasonable. At that time, the period of record was 1910–2003. A review of the extreme daily precipitation values from 1910 to 2003 in Fig. 3 shows that the only regions of the country that meet or exceed this 50.8-mm threshold are located in the Deep South and parts of California. In fact, the mean extreme threshold value for all grid cells is only 28 mm. As a result, the CEI was revised to utilize the 90th percentile value as determined by the distribution of the daily precipitation values in each 1° × 1° grid cell over the entire period of record. A simple sort and rank routine was implemented, and the value at the 90th percentile position of the distribution is used as the extreme threshold value. This ensures that each grid cell has extremes determined only by the data from within the grid cell and the combined results from all grid cells will reflect an overall average of approximately 10% at the extreme upper tail of the distribution. Data from each period or season are looked at independently, and separate calculations are made to determine the threshold values for extreme criteria with each period or season.

The third indicator in the CEI comprises extremes in

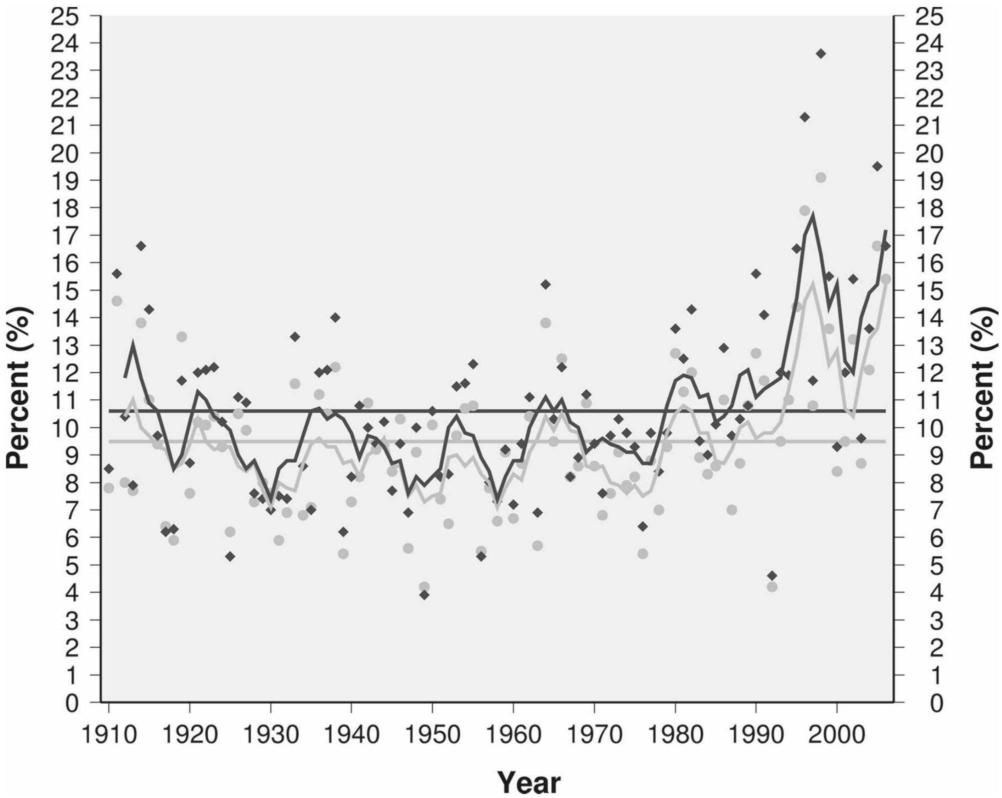

FIG. 2. Percentage of the contiguous United States with a much greater-than-normal proportion of precipitation derived from extreme 1-day precipitation events utilizing one station per 1° × 1° grid cell (black), one station per 0.5° × 0.5° grid cell (gray), and a 90% threshold for completeness from 1910 to 2006. Dots represent annual extreme values, curves depict the 5-yr moving averages, and straight lines are the period of record averages.

the PDSI based on the lowest and highest 10th percentile value of the distribution. Operationally, this can be determined by finding PDSI values that exceed ±3 (Palmer 1965). In practice, this is not necessarily the case. One of the limitations in using this index is related to the calibration period (1931–90), which is used to compute the long-term mean values for the various parameters utilized in the index. The distribution of PDSI values across all climate divisions over the period of record shows that the extreme percentile values are not ±3 in many cases. Others have identified this problem and suggested self-calibration for some of the constants involved in the calibration of the PDSI for the location in which the Palmer indices are being computed (Wells et al. 2004). At the present time, the PDSI constants are the same for all locations across the country, although they were originally computed for the Kansas/Iowa area. This difference affects the statistical distribution of the index. Since the CEI is based on evaluating the upper and lower 10% of the PDSI distribution, the resulting solution involved determining the lowest and highest 10th percentile value for each climate division rather than assuming threshold values of ±3. This new method is similar to what was accomplished with the revised fourth indicator. Upon implementation of the new threshold criteria for the period 1910–2003, the resulting "severe drought" threshold values ranged from −1.7 to −3.9 and "severe moisture" surplus values ranged from 1.3 to 3.9.

2) REVISED METHODOLOGY

With the potential addition of many new stations across the United States, a new approach was developed for use with the daily precipitation data that utilizes one station per grid cell for the entire period of record. The original CEI, although limited in the number of stations used, averaged together any station values located in the same grid cell. This methodology is not ideal, especially when considering stations that may or may not receive precipitation resulting from convective scenarios. In the revised method, the selected station from each grid cell possessed the fewest number of missing days in combination with the established period of record requirements (at least 90% complete) from

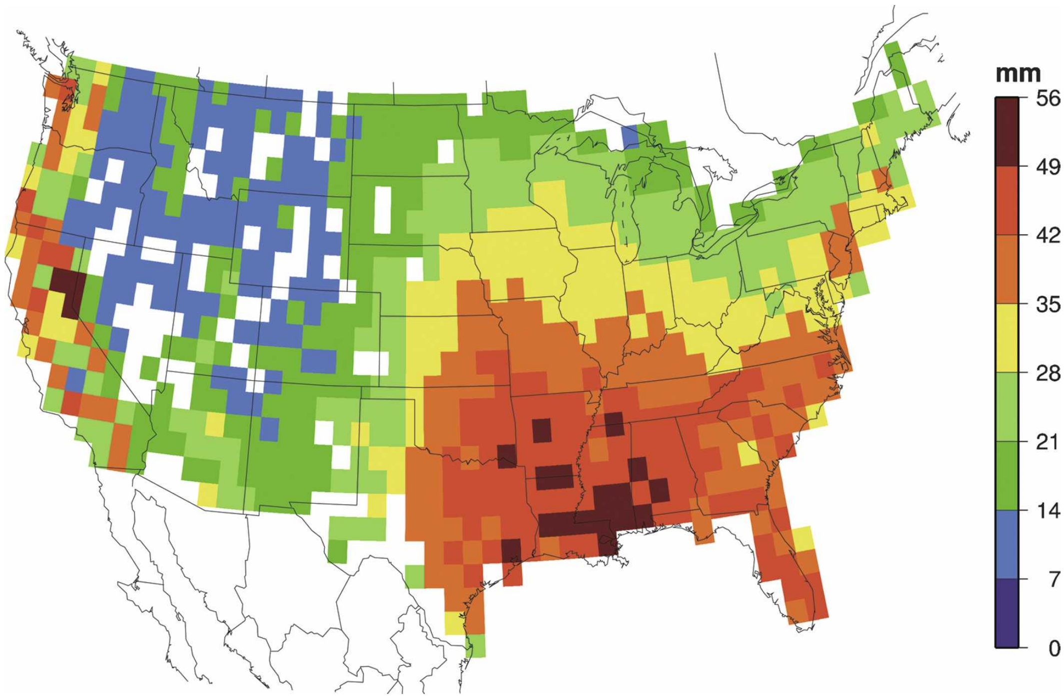

FIG. 3. Ninetieth percentile values of daily precipitation for each 1° × 1° grid cell from 1910 to 2003 using a 65% completeness threshold to improve spatial coverage in the western United States.

the other methods. More than 600 stations/grid cells were useable under these constraints. Results indicated that extreme percentages early in the century were sometimes greater than the expected 10% value and again from the late 1970s to the present, with extremes during the later period being the most dramatic (Fig. 2). These results were consistent with results from the original CEI as well as those from other studies of heavy and extreme precipitation in the United States (Karl and Knight 1998). Extremes detected from this method early in the century can be attributed to the addition of pre-1948 station data into the analysis.

4. Results

Each indicator selected for use in the CEI was chosen based on its reliability, length of record, data availability, and relevance to changes in climate extremes. Table 1 shows the definition of the revised CEI and provides a comparison with the original index. If we add results from the 90th and 10th percentiles in the individual indicators and subsequently average the indicators to form the combined CEI (Fig. 4), we see a U-shaped variation over the period in the mean. The interpretation of the changes in the combined indicator components of the CEI gives no information about the sign of the extremes or whether the changes are associated with extremes below the 10th percentile or above the 90th percentile. It does provide useful information as to what percentage of the contiguous United States experienced extremes of this type over time. Beyond this, the combined CEI should not be viewed as a standalone tool to determine the temporal characteristics in observed extremes. Changes in extremes may relate to changes in the mean and variance of a distribution in

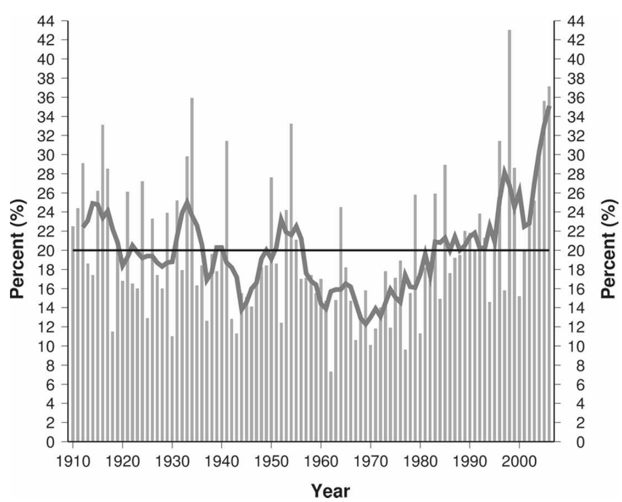

FIG. 4. The U.S. Climate Extremes Index annual period from 1910 to 2006. Bars represent annual extreme values, the dark curve depicts the 5-yr moving average, and the straight line is the period of record average.

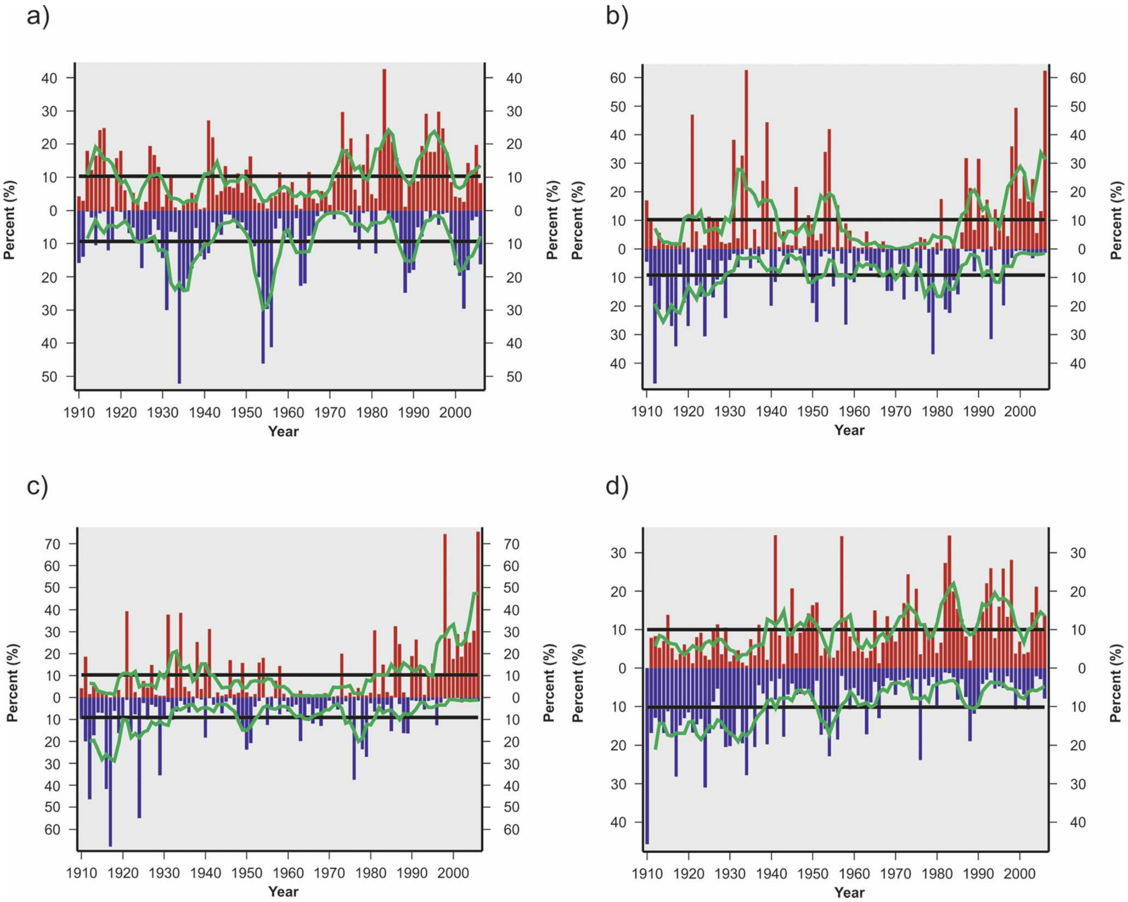

FIG. 5. Percentage of the conterminous U.S. area (a) in severe drought (blue) and severe moisture surplus (red) with (b) much below- (blue) and much above-normal (red) monthly mean maximum temperatures, (c) much below-normal (blue) and much above-normal (red) monthly mean minimum temperatures, and (d) a much greater-than-normal number of days without precipitation (blue) and days with precipitation (red) for the annual period from 1910 to 2006. Green curves represent 5-yr moving average values and straight black lines depict the period of record averages. (Note: scales vary for each figure.)

complicated ways. This points out the confounding nature of the CEI and the difficulty of trying to interpret the cause of abnormally high or low values; for example, it could be due to a trend or it could occur without a change in the mean but a real increase in variance. As a result, we have provided separate plots of the individual indicator components so as to view these characteristics without misinterpreting their combined meaning. A companion paper to the revised CEI, being prepared for submission, addresses these issues and offers a new solution for viewing the combined results.

a. Annual

The revised annual CEI, shown in Fig. 4, illustrates a general decrease in extremes with large variations from 1910 to the 1960s, then a steady increasing trend in extremes beginning in the early to mid-1970s. This corresponds with the time when the atmospheric circulation over North America and the Pacific underwent a significant change (Trenberth 1990; Trenberth and Hurrell 1994) and area-average temperatures started to increase. Over the most recent 10-yr period (1997–2006), there has been considerable year-to-year variability in the percent of the United States affected by extremes, with 5 of the 15 most extreme years on record occurring since 1997. Shorter-lived periods with high CEI values are evident during the 1930s and the 1950s. These correspond to periods of widespread extreme drought and above-normal temperatures in the United States. Figure 5a illustrates that over 50% of the CONUS was affected by much below-normal PDSI during the peak of the 1930s drought and about 45% in the mid-1950s. At the height of the most recent significant drought event early in this decade, only about 30% of the CONUS experienced much below-normal PDSI.

During the 1930s and 1950s drought periods, we see that extremes in maximum temperature are greater than those observed with minimum temperatures (Figs. 5b and 5c). During the two most recent and less severe drought periods in the 1980s and 2000s, extremes in both maximum and minimum temperatures are elevated. This implies that the diurnal temperature range during the first two drought events was likely larger than was experienced in the most recent drought events. This is in agreement with the findings in Vose et al. (2005) that, from 1950 to 2004, a significant decrease in diurnal temperature range was observed on a global scale, with much of this decrease occurring during the first half of this period. It can be seen in Figs. 5b and 5c that, since the 1980s, extremes in much above-normal mean maximum and mean minimum temperature remain high or have continued to increase. Increases in frequency of much above-normal maximum and minimum temperatures are consistent with characteristics of a warming climate (Houghton et al. 2001; Meehl et al. 2000), although the increase in observed warming is more dramatic over time in minimum temperatures than for maximum temperatures (Easterling et al. 1997; Vose et al. 2005). For the period 1979–2004, Vose et al. (2005) found similar increases in minimum and maximum temperature, which subsequently muted the diurnal temperature range trend. From the late 1970s to the mid-1980s a period of cooling across the eastern United States was evident and is consistent with the Pacific–North American teleconnection pattern (PNA) during that time [Trenberth (1990); the PNA is one of the most prominent modes of low-frequency variability in the Northern Hemisphere extratropics (for additional information on the PNA, see http://www.cpc.ncep.noaa.gov/data/teledoc/pna.shtml)].

Also of interest is the period of increased much below-normal mean maximum and minimum temperatures from 1910 to about 1930 (Figs. 5b and 5c). Significant drought during the 1930s and 1950s may have contributed to a decrease in much below-normal mean maximum and minimum temperatures since droughts are strongly correlated with warm extremes in maximum and minimum temperatures (DeGaetano and Allen 2002). In 1934, about 64% of the conterminous United States experienced much above-normal maximum temperatures, the highest percentage for any year since 1910. For the same year, the PDSI indicator shows about 52% of the United States was affected by drought, also the most extreme percentage noted during this period of record.

The fourth indicator analyzes extremes in the proportion of precipitation derived from extreme 1-day events for a period/season. It is important to note that trends in annual precipitation across the country since 1910 have been on the rise with an average increase of about 8.13 mm (0.32 inches) per decade across the United States. Similar results were noted in Groisman et al. (2004) using a 2.5° × 3.5° grid. In Fig. 2, we observe a steady increase in much above-normal proportion of 1-day precipitation events to total precipitation from the early 1970s to about 1998. Extremes in 1-day precipitation have been above the expected value of 10% in 10 of the 12 years over the period 1995–2006. These results suggest that extremes in much above-normal proportion of 1-day precipitation are on the rise, which is supported by findings in Groisman et al. (2001) and Karl and Knight (1998).

The fifth indicator examines extremes in the number of days with and without precipitation. An elevated period of extremes in the number of days without precipitation is evident from the early 1900s to about 1940, and a gradual increase in days with precipitation has occurred from the 1940s through the 1980s. From the 1980s to the present, we see some periods of consistently elevated extremes in the number of days with precipitation yet with no apparent increase or decrease in overall trend (Fig. 5d). Not surprisingly, the number of days without precipitation increased during the droughts of the 1950s and to a lesser extent during the droughts of the 1980s and 2000s. Trends in 1-day precipitation events show a tendency toward more days with large 1-day precipitation totals (Karl and Knight 1998; Easterling et al. 2000). This supports the increase in extremes observed in both the fourth and fifth indicators.

b. *Other periods*

In addition to the annual CEI, the warm season CEI graph in Fig. 6a also indicates increasing trends in extremes since the early 1970s. Notable periods of short-duration extremes are evident for the warm season in the late 1910s, the 1930s, and also the 1950s. This can be attributed in part to extremes in monthly mean maximum temperatures as well as periods of extreme drought as determined using the PDSI.

Extremes observed in the summer CEI show a steady increase from about 1970 to 1990 with a secondary rise from the mid-1990s to the present (Fig. 6b). A portion of the most recent elevated extremes period during the summer months can be attributed to a steady and dramatic increase in much above-normal monthly mean minimum temperatures since the mid-1970s (Fig. 7a). Extremes in much above-normal mean maximum temperatures are also increasing during this time, yet much below-normal mean maximum temperature extremes for three summers over the past 15 years (1992, 1993,

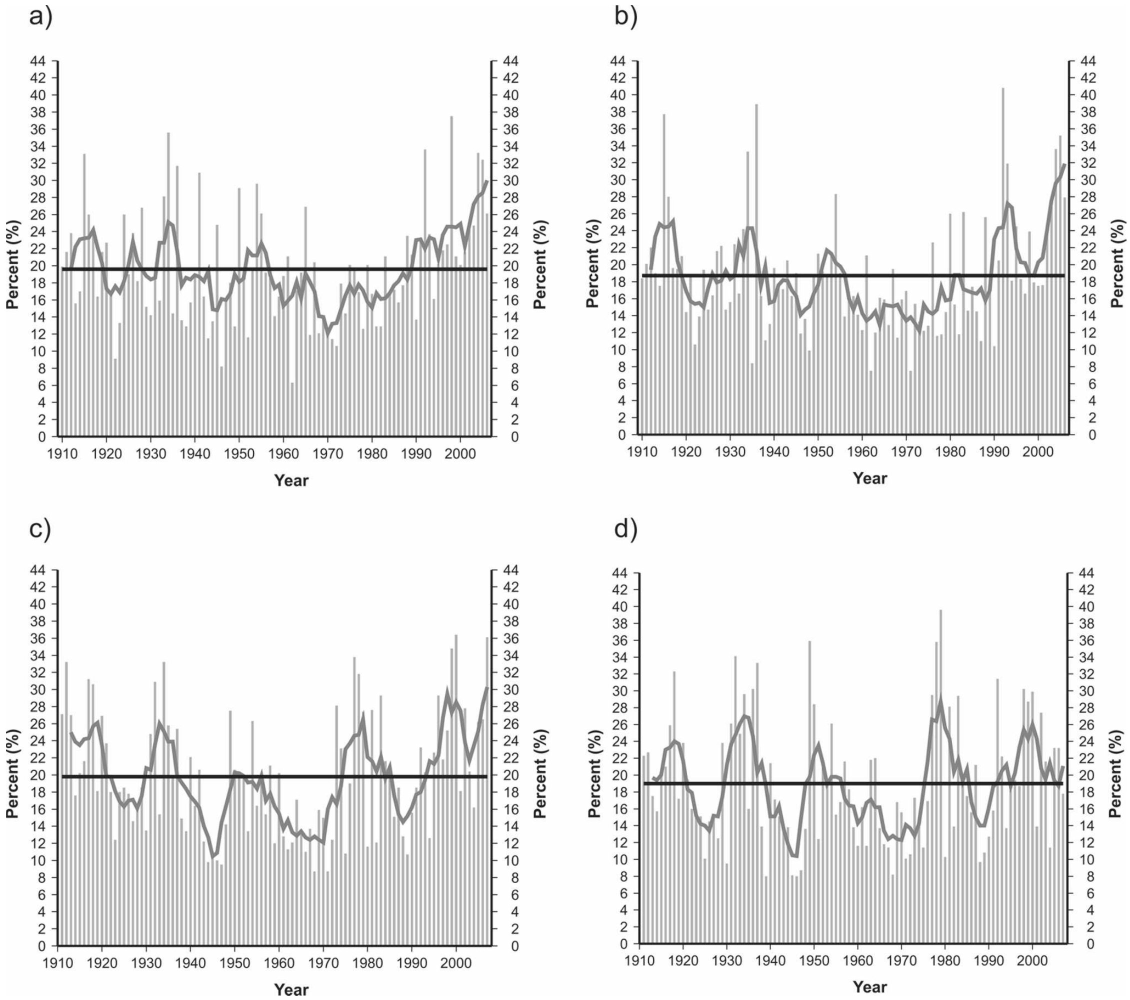

Fig. 6. As in Fig. 4 but for the (a) warm season (April–September) and (b) summer (June–August) from 1910 to 2006 and (c) cold season (October–March) and (d) winter (December–February) from 1911 to 2007.

and 2004) were three to five times the expected value (Fig. 7b). The eruption of Mt. Pinatubo in 1991 was perhaps a contributor to the observed extremes in minimum temperature during 1992. Cold extremes noted in 2004 can be attributed to an upper-level trough entrenched over the Great Lakes from April to August of that year.

The cold season CEI has large amplitude fluctuations over time with a periodicity of about 20 yr (Fig. 6c). Even with the large fluctuations, an overall trend toward increasing extremes for this period is noticeable from the mid-1940s to the present. Recent extremes in much above-normal mean maximum and minimum temperatures during the cold season are significant and consistent with those seen during the annual, summer, warm, and hurricane seasons (Figs. 7c and 7d). Also of interest are significant much below-normal extremes periods during the early 1900s and again in the 1970s.

Similarly, the winter CEI also shows a wide variation in extremes over time, yet very little overall trend toward increasing or decreasing extremes (Fig. 6d). One might infer from these results that the cooler season periods (winter and cold seasons) do not indicate climate change as consistently as the warmer season periods (summer and warm seasons), which illustrate a more steady increase in extremes since the 1970s.

5. Summary and recommendations

The CEI was first presented in 1995 as a framework for quantifying observed changes in climate within the contiguous United States. The index was originally constructed using a set of conventional climate extremes indicators from a relatively limited amount of station records. In this revised index, additional temperature and precipitation stations were added to improve spatial coverage without compromising completeness of

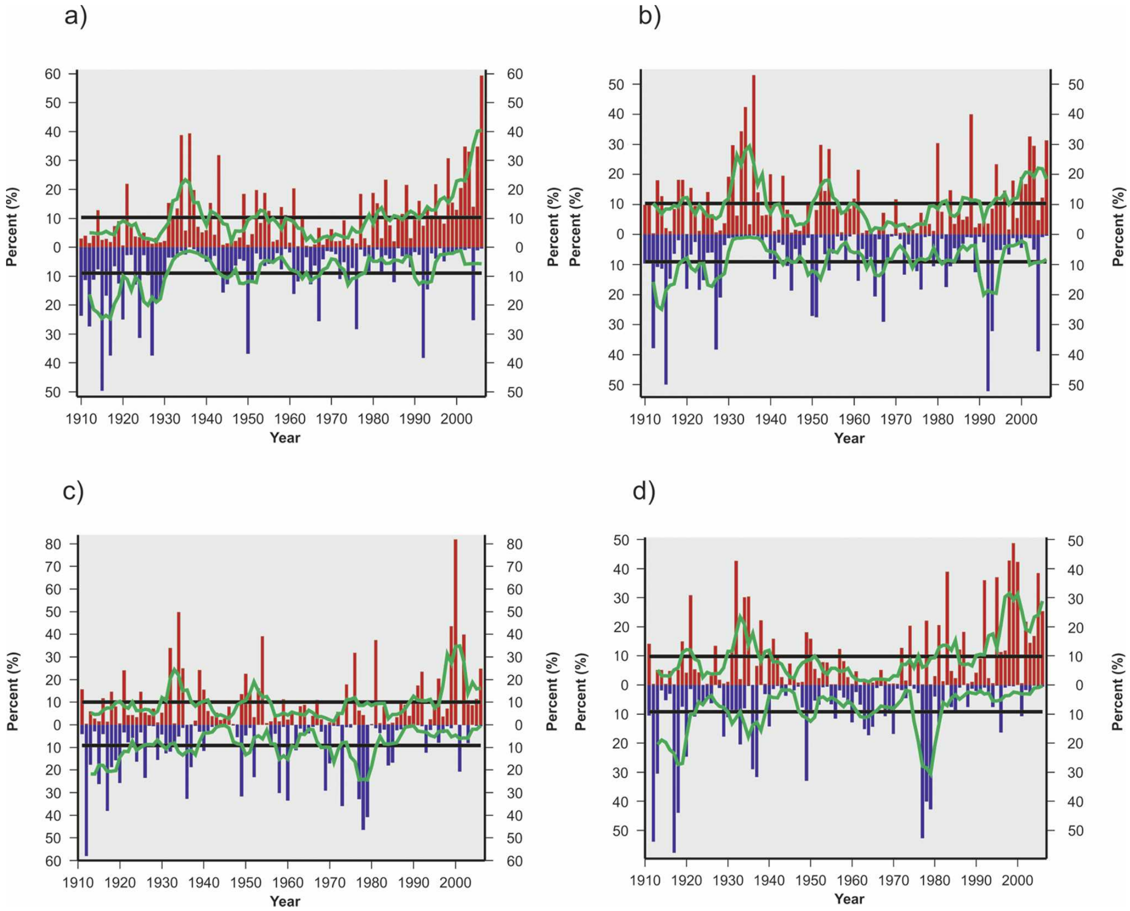

FIG. 7. The percentage of the conterminous U.S. area with (a) with much below- (blue) and much above-normal (red) monthly mean minimum temperatures and (b) much below-normal (blue) and much above-normal (red) monthly mean maximum temperatures for the summer season (June–Aug) from 1910 to 2006 and (c) much below-normal (blue) and much above-normal (red) monthly mean maximum temperatures and (d) much below-normal (blue) and much above-normal (red) monthly mean minimum temperatures for the cold season (Oct–Mar) from 1911 to 2007. Green curves represent 5-yr moving average values and straight black lines depict the period of record averages. (Note: scales vary for each figure.)

data. The additional data also support the calculation of the revised CEI over eight separate periods (spring, summer, autumn, winter, annual, cold season, warm season, and YTD) instead of the single annual analysis that was performed with the original index. Near-real-time data have also been incorporated into the index, which allow the CEI to be operationally updated every month.

Comparing results from the original annual CEI with the revised annual CEI, we see that elevated extreme climate periods coincide during the 1930s, the 1950s, and from the early 1970s to the present (Figs. 4 and 8). The original CEI attributed extremes in the 1930s and 1950s primarily to the increasing frequency of much above-normal mean maximum temperatures, days without precipitation, as well as long-term drought severity. For the most recent period, attribution of extremes was primarily the result of the increases in frequency of high mean maximum and minimum temperatures and the decrease in frequency of low mean maximum and minimum temperatures. Other contributing factors were the increase in frequency of long-term drought severity and moisture excess, the frequency of extreme 1-day precipitation events, and a much greater-than-normal number of days with precipitation. Results from the revised CEI illustrate that these extreme climate variation periods can also be attributed to the same precipitation and temperature indicators. In fact, the area of the CONUS experiencing extremes in both mean maximum and minimum temperature since 1995 has been consistently extensive.

Revised CEI results indicate that for the annual, summer, and warm seasons the percent of the contiguous United States experiencing extreme conditions has

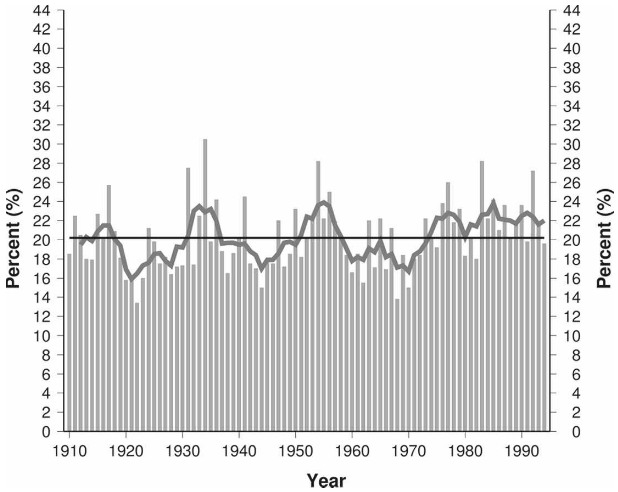

FIG. 8. The original U.S. CEI for the annual period from 1910 to 1994.

been generally increasing since the early 1970s. Significant contributors to this include increases in monthly mean maximum and minimum temperatures over the past 30 to 40 years. Results from the cold season CEI indicate a possible increasing trend in extremes since the 1940s with large season-to-season fluctuations. Little to no trend in extremes was noted for other standard periods, including the winter season. Graphs of the most current CEI and the individual indicators that are comprised in the CEI may be viewed at the NCDC CEI Web site (http://www.ncdc.noaa.gov/oa/climate/research/cei/cei.html).

Recommendations for future work with the CEI include the addition of other possible climate extremes indicators, as additional data sources become available or accessible (e.g., hail occurrence, tornado frequency/intensity, wind events). Much work has already gone into the development of a landfalling hurricane wind speed indicator. It is likely that a separate paper will be presented, which will delineate the different aspects of this indicator and how it relates to the current index. A Climate Extreme Impacts Index is also recommended and may incorporate the landfalling hurricane wind speed indicator. This index would build on the current version of the CEI while incorporating components related to economic and population considerations. In addition, a regional CEI may be appropriate for smaller-scale applications since the current CEI does not capture the variability in extremes that exists on a regional scale across the nation. Creation of an Alaskan CEI could also be beneficial as there is much interest in polar region climate change and documented changes in extremes in temperature and precipitation for this region have been significant in recent years.

In a companion study, the causes of the observed variations of the CEI are evaluated using climate model simulations of the climate of the twentieth century. Results from model simulations with changing external forcing are compared with those from control model simulations. This evaluation will be presented in a future paper.

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APPENDIX

The U.S. Climate Extremes Index: Definitions and Calculations

The U.S. CEI is the annual arithmetic average of the following five indicators of the percentage of the conterminous U.S. area:

1) the sum of (i) percentage of the United States with maximum temperatures much below normal and (ii) percentage of the United States with maximum temperatures much above normal;
2) the sum of (i) percentage of the United States with minimum temperatures much below normal and (ii) percentage of the United States with minimum temperatures much above normal;
3) the sum of (i) percentage of the United States in severe drought based on the PDSI and (ii) percentage of the United States with severe moisture surplus based on the PDSI;
4) twice the value of the percentage of the United States with a much greater-than-normal proportion of precipitation derived from extreme 1-day precipitation events;
5) the sum of (i) percentage of the United States with a much greater-than-normal number of days with precipitation and (ii) percentage of the United States with a much greater-than-normal number of days without precipitation.

a. Monthly mean maximum/minimum temperature indicators (1 and 2 from definition above)

For each month or period in the analysis, station temperature data from within the same grid cell are averaged together using a simple arithmetic mean, and the resulting average is used to represent that $1° \times 1°$ cell. Only grid cells containing station data are used to approximate the percentage of the U.S. area that is extreme. For a seasonal or annual calculation, all gridded monthly values are evaluated to determine if they meet the 90% completeness requirement within each seasonal or annual period as well as for the entire period of

FIG. A1. The U.S. standard regions for temperature and precipitation.

record. If a given grid cell passes this test, these values are averaged together with all other monthly values during the period of interest. These newly calculated period averages are then sorted and ranked. From this new distribution, the 90th and 10th percentile values are determined and extreme seasons/periods are identified. For each of the nine standard regions (Karl and Koss 1984; Fig. A1), the "extreme" grid values are identified for this period and the proportion of the area of the region affected by extreme temperatures is calculated for each year in the analysis period. This fraction is then area weighted among the other eight regions and a national extreme fraction is computed for each period or season. This area-weighting scheme helps to offset the possibility of biasing the national value toward regions of the country with higher station densities. Extreme percentages across the entire CONUS are tallied and compared with all other years in the period of record.

b. PDSI indicator (3 from definition above)

The third indicator in the CEI comprises extremes in the Palmer Drought Severity Index calculated as the lowest and highest 10th percentile value of the distribution. The PDSI database consists of serially complete climate division data from 1900 to the present, with values typically ranging within ±4. For consistency with the other CEI steps, this analysis only includes data from 1910 to the present. PDSI values from within each division are averaged together for the period of interest, sorted, and ranked to identify the extreme (10th and 90th percentile) threshold values. Once these values have been identified for each division, individual periods or seasons are identified as "extreme" and the area of each extreme division is summed together and compared to the total area of the United States over the entire period of record.

c. Daily precipitation indicators (4 and 5 from definition above)

As with the temperature indicators, the percentage of the contiguous United States affected by extreme precipitation is determined from the grid cells that contain station data. The same area-weighting scheme is used to achieve a national area percentage for the extreme precipitation indicators, but on a daily time scale and for one station per grid cell. When multiple stations exist within the same grid cell, the station with the longest and most complete period of record is selected to represent this area for both the fourth and fifth indicators. The fourth indicator is unique in that only the top 10% of occurrences is considered, instead of the top and bottom 10% as in the other steps. To ensure consistency among all the steps, this indicator is doubled when combined with the other indicators to be comprised in the CEI. All of the extreme total daily values are summed together within a grid cell for a given period or season and compared to the total amount of precipitation that occurred during that same period. This "period" proportion is compared to all other proportions for the same grid cell for each year in the analysis. Newly calculated values are sorted and ranked, and an extreme proportion is determined based on the 90th percentile proportion value. As with the temperature indicators, the proportion of area affected by extremes is computed on a regional basis with subsequent calculation of a weighted national extreme average for each period or season.

In the fifth indicator, the number of days with precipitation is defined as those days that report at least a trace amount of precipitation on any given day. For each period or season over the entire period of record and for each grid cell, the total number of days with (without) precipitation is tallied, counts are sorted, ranked, and a threshold for the 90th (10th) percentile value is computed. Tallies for all periods/seasons are compared to this threshold count value and extreme periods are determined for each grid cell. As with the temperature indicators, the proportion of extreme grids to nonextreme grids from within one of the nine standard regions is determined for each year in the analysis. This fraction is weighted among the other regions and a national extreme average is computed for each period or season.

d. Calculation of the CEI based on the results from the five indicators

Once the percent area of the contiguous United States that has been determined to be extreme for each period/season and an indicator has been calculated, the composite CEI can be calculated for each year over the entire period of record. The five indicator values for each period/season are given equal weight and are averaged together. The resulting CEI averages are then plotted to indicate the percent area of the contiguous United States that is considered extreme based on the combined effects of the five indicators outlined above.

REFERENCES

DeGaetano, A. T., and R. J. Allen, 2002: Trends in twentieth-century temperature extremes across the United States. *J. Climate,* **15,** 3188–3205.

Easterling, D. R., and Coauthors, 1997: Maximum and minimum temperature trends for the globe. *Science,* **277,** 364–367.

——, J. L. Evans, P. Ya. Groisman, T. R. Karl, K. E. Kunkel, and P. Ambenje, 2000: Observed variability and trends in extreme climate events: A brief review. *Bull. Amer. Meteor. Soc.,* **81,** 417–425.

Groisman, P. Ya., R. W. Knight, and T. R. Karl, 2001: Heavy precipitation and high streamflow in the contiguous United States: Trends in the twentieth century. *Bull. Amer. Meteor. Soc.,* **82,** 219–246.

——, ——, ——, D. R. Easterling, B. Sun, and J. H. Lawrimore, 2004: Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *J. Hydrometeor.,* **5,** 64–85.

Houghton, J. T., L. G. Meira Filho, and B. A. Callendar, Eds., 1995: *IPCC Second Assessment—Climate Change 1995.* Cambridge University Press, 572 pp.

——, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, Eds., 2001: *Climate Change 2001: The Scientific Basis.* Cambridge University Press, 881 pp.

Karl, T. R., 1986: The sensitivity of the Palmer Drought Severity Index and Palmer's Z-index to their calibration coefficients including potential evapotranspiration. *J. Climate Appl. Meteor.,* **25,** 77–86.

——, and W. J. Koss, 1984: Regional and national monthly, seasonal, and annual temperature weighted by area 1895–1983. National Climatic Data Center Tech. Rep. Historical Climatology Series 4-3, 38 pp.

——, and C. N. Williams Jr., 1987: An approach to adjusting climatological time series for discontinuous inhomogeneities. *J. Climate Appl. Meteor.,* **26,** 1744–1763.

——, and R. W. Knight, 1998: Secular trends of precipitation amount, frequency, and intensity in the United States. *Bull. Amer. Meteor. Soc.,* **79,** 231–241.

——, C. N. Williams Jr., P. J. Young, and W. M. Wendland, 1986: A model to estimate the time of observation bias associated with monthly mean maximum, minimum and mean temperatures for the United States. *J. Climate Appl. Meteor.,* **25,** 145–160.

——, H. F. Diaz, and G. Kukla, 1988: Urbanization: Its detection and effect in the United States climate record. *J. Climate,* **1,** 1099–1123.

——, C. N. Williams Jr., F. T. Quinlan, and T. A. Boden, 1990: United States Historical Climatology Network (HCN) serial temperature and precipitation data. Department of Energy, Oak Ridge National Laboratory Tech. Rep. ORNL/CDIAC-30, NDP-019/R1, 389 pp.

——, R. W. Knight, D. R. Easterling, and R. G. Quayle, 1996: Indices of climate change for the United States. *Bull. Amer. Meteor. Soc.,* **77,** 279–292.

Meehl, G. A., F. Zwiers, J. Evans, T. Knutson, L. Mearns, and P. Whetton, 2000: Trends in extreme weather and climate events: Issues related to modeling extremes in projections of future climate change. *Bull. Amer. Meteor. Soc.,* **81,** 427–436.

Palmer, W. C., 1965: Meteorological drought. U.S. Weather Bureau Research Paper 45, 65 pp.

Quayle, R. G., D. R. Easterling, T. R. Karl, and P. Y. Hughes, 1991: Effects of recent thermometer changes in the cooperative station network. *Bull. Amer. Meteor. Soc.,* **72,** 1718–1723.

Ross, T. F., 2004: Climate database modernization program provides access to historical data and records: An overview of various projects. *Extended Abstracts, 14th Conf. on Applied Climatology,* Seattle, WA, Amer. Meteor. Soc., 1-1. [Available online at http://ams.confex.com/ams/pdfpapers/70836.pdf.]

Solomon, S., D. Qin, M. Manning, M. Marquis, K. Averyt, M. M. B. Tignor, H. Leroy Miller Jr., and Z. Chen, Eds., 2007: *Climate Change 2007: The Physical Science Basis.* Cambridge University Press, 996 pp.

Trenberth, K. E., 1990: Recent observed interdecadal climate changes in the Northern Hemisphere. *Bull. Amer. Meteor. Soc.,* **71,** 988–993.

——, and J. W. Hurrell, 1994: Decadal atmosphere-ocean variations in the Pacific. *Climate Dyn.,* **9,** 303–319.

Vose, R. S., D. R. Easterling, and B. Gleason, 2005: Maximum and minimum temperature trends for the globe: An update through 2004. *Geophys. Res. Lett.,* **32,** L23822, doi:10.1029/2005GL024379.

Wells, N., S. Goddard, and M. J. Hayes, 2004: A self-calibrating Palmer Drought Severity Index. *J. Climate,* **17,** 2335–2351.