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Temporal variations of extreme precipitation events in the United States: 1895–2000

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[1] A newly available data set of daily precipitation observations was used to study the temporal variability of the frequency of short-duration extreme precipitation events for 1895–2000 in the conterminous United States. Event durations of 1, 5, 10, and 30 day and return periods of 1, 5, and 20 year were analyzed. For all combinations of duration and return period, heavy precipitation frequencies were relatively high during the late 19th/early 20th Centuries, decreasing to a minimum in the 1920s and 30s, followed by a general increase into the 1990s. The frequencies at the beginning of the 20th Century were nearly as high as during the late 20th Century for some combinations of duration and return period, suggesting that natural variability cannot be discounted as an important contributor to the recent high values. Extensive quality control of data and Monte Carlo testing was performed to provide confidence in the reality of the early period high frequencies. *INDEX TERMS:* 1833 Hydrology: Hydroclimatology; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620). **Citation:** Kunkel, K. E., D. R. Easterling, K. Redmond, and K. Hubbard, Temporal variations of extreme precipitation events in the United States: 1895–2000, *Geophys. Res. Lett.*, *30*(17), 1900, doi:10.1029/2003GL018052, 2003.

1. Introduction

[2] A number of studies have found an unambiguous upward trend in the frequency of heavy to extreme precipitation events in parts of the United States. *Karl et al.* [1995] found that the contribution to total annual precipitation of 1-day precipitation events exceeding 50.8 mm increased from about 9% in the 1910s to about 11% in the 1980s and 1990s. This was coincident with a general upward trend in total precipitation. In a more definitive study, *Karl and Knight* [1998] confirmed that the observed increase in total precipitation was due in large part to increases in the intensity of heavy to extreme precipitation events. *Kunkel et al.* [1999] examined trends in multi-day extreme precipitation events, finding statistically significant upward trends in 1-year return period, 7-day duration events of about 3% per decade and in 5-year, 7-day events of about 4% per decade since 1931. *Groisman et al.* [2001] reported a 50% increase during the 20th Century in the frequency of days with precipitation exceeding 101.6 mm in the upper Midwest U.S. The results of these and other studies led the Intergovernmental Panel on Climate Change (IPCC) to conclude that "it is likely that there has been a widespread increase in heavy and extreme precipitation events in regions where total precipitation has increased (e.g., the mid- and high-latitudes of the Northern Hemisphere)" [*Cubasch et al.*, 2001]. In addition, the IPCC states that it is highly likely that increases in heavy precipitation extremes will occur during the 21st Century [*Houghton et al.*, 2001].

[3] A common limitation of these and other studies is that they used data beginning in the middle portion of the 20th Century or used a restricted set of stations [e.g., *Karl et al.*, 1995; *Kunkel et al.*, 1999] not representing many regions of the U.S. The reason for this has been a lack of digitally available data. Although the National Weather Service Cooperative Observer Network (COOP) has been in operation since the late 19th century, the routine digitizing of observations from hand-written forms began in 1948. A recent effort to digitize all pre-1948 COOP data has resulted in an enhanced set of daily temperature and precipitation data for the U.S. starting in the late 1800s [*CDMP*, 2001]. The availability of these pre-1948 daily data affords an opportunity to perform studies with unprecedented detail, extending back to the late 1800s, of trends in short duration extreme events. Because industrial development was minimal until about midway through the 20th Century, the earlier record reflects mainly natural variability. Thus, this study may provide important insights into natural and anthropogenically-forced variability.

[4] A very preliminary analysis was presented by *Kunkel* [2003]. Here we present a more comprehensive analysis, including an examination of the statistical significance of

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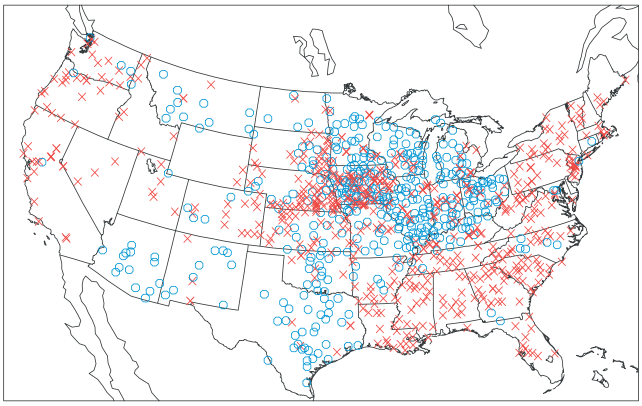

Figure 1. Location of stations with less than 10% missing daily precipitation data for 1895–2000. The symbol 'o' (in blue) indicates that long-term data were available prior to CDMP while the symbol 'x' (in red) indicates newly available long-term stations.

results and of the quality of the precipitation data in the early part of the record.

2. Analysis

[5] A set of stations with less than 10% missing precipitation data for 1895–2000 was identified; this set consists of 920 stations distributed as shown in Figure 1. New long-term stations that are now available as the result of the recent keying project are indicated by the symbol 'x' in red. Prior to this project, there were very few stations in the southeast, along the east and west coasts, and in the intermountain west. Although there are still areas with a low density of long-term stations, particularly in Wyoming, the Great Basin, Idaho, and California, all western states now have at least 3 such sites and the eastern and Gulf Coast regions have a dense coverage.

[6] The method of trends assessment followed the recent study by *Kunkel et al.* [1999]. Extreme events were defined by duration and return period. The event durations were chosen to be 1, 5, 10, and 30 days. The event thresholds were those associated with return periods of 1, 5, and 20 years. These thresholds were determined empirically from each station's own climatology using a partial duration series analysis. The specific procedure is as follows. The event of rank 1 is first determined. The days comprising this event are removed from the data time series. The second-ranked event is then determined by finding the highest-ranking event in the remaining data. The procedure continues in an iterative fashion until N events have been identified where $N = M_y/R$, where M_y is the number of years of data and R is the return period in years. For example, for a station with 100 years of data and for an analysis of 5-yr return period events, 20 events are identified. Therefore, the threshold so determined is exceeded 20 times in 100 yrs for an average return period of 5 yrs. Events were assigned to the calendar year of the beginning day of the event. Occasionally, multi-day events crossed year boundaries.

[7] For each station, the annual number of extreme events was counted. To assess national trends for the conterminous U.S., station values were arithmetically averaged for climate divisions. The climate division values were then averaged with area weighting to derive state values (there were a small number of climate divisions without any long-term stations and a few state values are averages of only some of their climate divisions). Finally, state values were averaged with state area weighting to derive national values. Thus, areas of high or low station density are not unduly weighted or ignored, respectively. This average will be referred to as the Extreme Precipitation Index (EPI). This index is simply the area-weighted national average frequency (per station) of extreme events for each year. For 1-, 5-, and 20-year return periods, the average values of this index are 1, 0.2, and 0.05, respectively.

[8] Quality control (QC) of the CDMP precipitation data consisted of the identification of "outliers" and manual assessment of the validity of each outlier by a climatologist. One set of outliers consisted of all daily values exceeding 254 mm. In addition, initial results (see below) indicated that the period of 1895–1910 exhibited interesting behavior and further QC concentrated on this period. A second set of outliers was identified for this period. Based on spatial consistency with nearby stations, each daily value was given a quality score. Those values with the lowest quality scores were considered outliers and then manually assessed. QC of the entire CDMP dataset is ongoing.

3. Results

[9] Figure 2 shows the EPI time series. These time series are smoothed with a 7-yr moving average filter to remove much of the sub-decadal variability and facilitate the viewing of trends and persistent anomalies. High frequencies in the 1980s and 1990s when coupled with very low frequencies in the 1920s–1930s and moderately low frequencies in the 1950s–1970s has resulted in statistically significant upward trends in other studies, such as those of *Karl and Knight* [1998] and *Kunkel et al.* [1999]. However, rather high frequencies of heavy precipitation events also occurred at the end of the 19th Century and in the early part of the 20th Century, producing an overall U-shape in the Figure 2 time series. The behavior is not identical for all combinations of return period and duration. For example, the peaks in the 1940s and 1980s are most prominent for multi-day durations while the early 20th Century peak is most prominent in the 1-day duration results. However, all combinations exhibit a general U-shape.

[10] Although the station density is much improved over what was previously available, the density is rather low in portions of the western U.S. Is it possible that this U-shaped feature is an artifact of sampling? This possibility was examined by analyzing more recent data using Monte Carlo sampling techniques. Specifically, a set of 4,349 stations with less than 5% missing data for 1971–2000 was identified. This set has much higher station density in the western U.S. The sensitivity to station density was examined by randomly selecting a single station in each box of a 4° latitude by 5° longitude grid, a density approximately equal to the least dense areas in the intermountain west in Figure 1, covering the entire U.S. The EPI was then computed for this thinned-out station network. This procedure was repeated 5000 times and the distribution of EPI

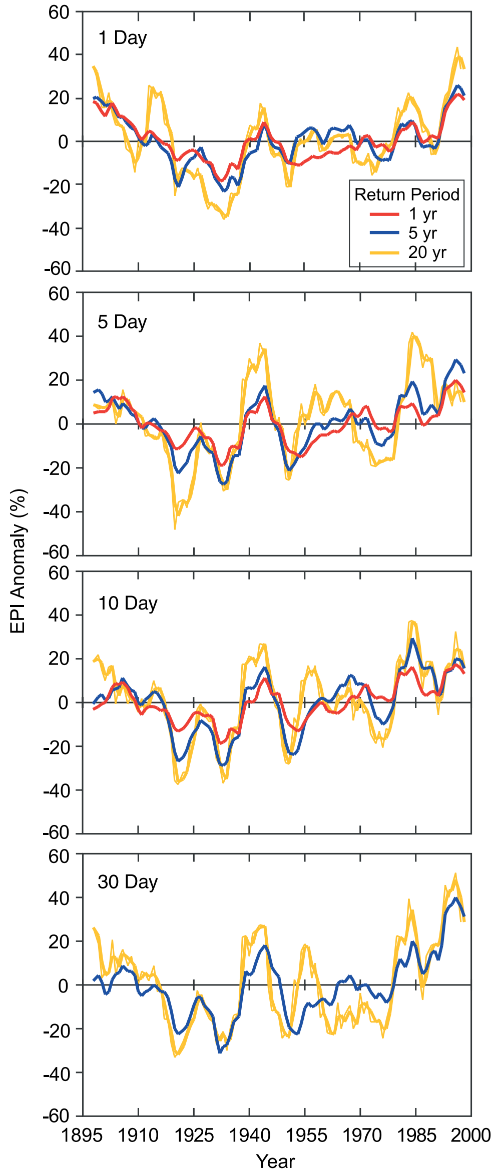

Figure 2. Time series of anomalies of the Extreme Precipitation Index, expressed in %, for various combinations of duration and return period. The time series have been smoothed with a 7-yr moving average filter. Return periods of 1 year (red), 5 years (blue), and 20 years (orange) are plotted on each graph.

values was examined. The results were insensitive to event duration but were quite sensitive to return period. The 95% confidence limits for decadal average values of the EPI were approximately ±6%, ±15%, and ±30% for 1-yr, 5-yr, and 20-yr return periods, respectively. Even though this test is more stringent than necessary since only a small portion of the U.S. has such low station densities, these values are used as an upper bound on the uncertainties. In Figure 1, the elevated frequencies in the early part of the record are 30–50% higher than the minima occurring in the middle part of the record and the 95% confidence limits between these two periods do not overlap for the 1-yr and 5-yr return periods. Thus, there is a very high likelihood that the elevated frequencies in the early part of the record are real and not

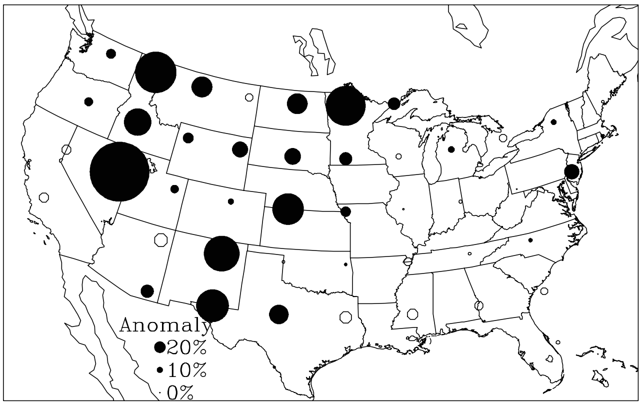

Figure 3. Map of frequency anomalies (compared to the period average) of the Extreme Precipitation Index during 1895–1905 for 1-day, 1-year events on a 4° latitude by 5° longitude grid. Filled-in (open) circles indicate positive (negative) anomalies.

an artifact of sampling for 1-yr and 5-yr return periods, but such a conclusion is less certain for the 20-yr return period results.

[11] As an example of the spatial patterns of the elevated frequencies in the early part of the record, frequency anomalies (based on the 1895–2000 period average) were calculated for the 4° latitude by 5° longitude grid used in the Monte Carlo analysis as an arithmetic average of all stations within each grid box. The results for 1-day duration, 1-year return period events for two 11-year periods, 1895–1905 and 1990–2000, are shown in Figures 3 and 4, respectively. In the earlier period, stations with large positive frequency anomalies are located primarily in the central and western portions. Anomalies are generally small in the eastern portion and somewhat negative along the Gulf Coast. Thus, there is a sharp contrast between the west and the Gulf Coast. The spatial distribution for other durations and return periods is qualitatively similar. In the latter period, positive frequency anomalies are widespread over much of the U.S. and the range in the magnitude of the anomalies is smaller

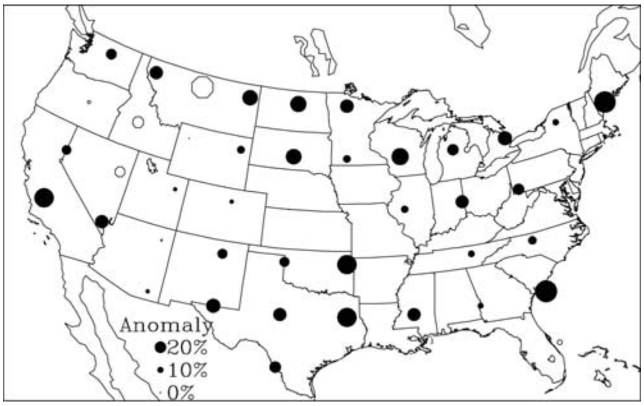

Figure 4. Map of frequency anomalies (compared to the period average) of the Extreme Precipitation Index during 1990–2000 for 1-day, 1-year events on a 4° latitude by 5° longitude grid. Filled-in (open) circles indicate positive (negative) anomalies.

than in the earlier period; thus, there is somewhat less regional variation in the latter period.

4. Discussion/Conclusions

[12] Frequencies of extreme precipitation events during 1895–1905 are above the 1895–2000 period averages for all durations and return periods. For 1-day duration events, frequencies during 1895–1905 are comparable in magnitude to frequencies in the 1980s and 1990s. For 5- and 10-day duration events, frequencies during 1895–1905 are only slightly smaller than late 20th Century values. *Kunkel et al.* [1999] had found elevated frequencies around 1900 for 7-day duration events in parts of the central U.S.; the results presented herein indicate that high frequencies also occurred in much of the western and northern U.S. This feature provides insight into the natural variability of extreme precipitation events. Since enhanced greenhouse gas forcing of the climate system was very small at that time, the elevated frequencies were most likely a consequence of naturally forced variability, although possible influences from land-use changes cannot be ruled out. For 1-day duration events, recent increases in frequencies are of comparable magnitudes to frequencies around the turn of the century, suggesting the possibility that natural variability could be an important contributor to the recent increases.

[13] The greater length of record used in this analysis, compared to many previous studies, establishes an important context for understanding recent changes in the U.S. For example, inspection of time series of extremes based on just the last 50–70 years lead to quite different qualitative conclusions than those based on the 107-yr record used here. Further insights may be gained in the future as other data sets become available. For example, the CDMP is now undertaking the keying of selected 19th Century records of U.S. daily climate observations taken prior to the establishment of the COOP. Although observational practices were not as standardized and thus homogeneity of record will be an issue, it may be possible to add a few decades to the century-long findings presented here.

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References

Climate Database Modernization Project (CDMP), Annual Report, available from the National Climatic Data Center, Asheville, NC, 8 pp., 2001.

Cubasch, U., G. A. Meehl, G. J. Boer, R. J. Stouffer, M. Dix, A. Noda, C. A. Senior, S. Raper, and K. S. Yap, Projections of future climate change. In: *Climate Change 2001: The Scientific Basis. Contributions of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, Cambridge Univ. Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp., 2001.

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

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (Eds.), *Climate Change 2001: The Scientific Basis. Contributions of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge Univ. Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp., 2001.

Karl, T. R., and R. W. Knight, Secular trends of precipitation amount, frequency, and intensity in the United States, *Bull. Am. Meteorol. Soc.*, *79*, 231–241, 1998.

Karl, T. R., R. W. Knight, D. R. Easterling, and R. G. Quayle, Trends in U.S. climate during the twentieth century, *Consequences*, *1*, 3–12, 1995.

Kunkel, K. E., North American trends in extreme precipitation, *Natural Hazards*, *29*, 291–305, 2003.

Kunkel, K. E., K. Andsager, and D. R. Easterling, Long-term trends in extreme precipitation events over the conterminous United States and Canada, *J. Clim.*, *12*, 2515–2527, 1999.

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