Changes in Intense Precipitation over the Central United States

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ABSTRACT

In examining intense precipitation over the central United States, the authors consider only days with precipitation when the daily total is above 12.7 mm and focus only on these days and multiday events constructed from such consecutive precipitation days. Analyses show that over the central United States, a statistically significant redistribution in the spectra of intense precipitation days/events during the past decades has occurred. Moderately heavy precipitation events (within a 12.7–25.4 mm day\(^{-1}\) range) became less frequent compared to days and events with precipitation totals above 25.4 mm. During the past 31 yr (compared to the 1948–78 period), significant increases occurred in the frequency of “very heavy” (the daily rain events above 76.2 mm) and extreme precipitation events (defined as daily and multiday rain events with totals above 154.9 mm or 6 in.), with up to 40% increases in the frequency of days and multiday extreme rain events. Tropical cyclones associated with extreme precipitation do not significantly contribute to the changes reported in this study. With time, the internal precipitation structure (e.g., mean and maximum hourly precipitation rates within each preselected range of daily or multiday event totals) did not noticeably change. Several possible causes of observed changes in intense precipitation over the central United States are discussed and/or tested.

1. Introduction

On average over the central United States, more than 70% of annual precipitation falls during ~25% of rain days with totals above 12.7 mm. Throughout this paper we shall refer to these days as “days with intense precipitation” to distinguish them from remaining 75% of rain events that can be loosely named as “light precipitation.” The U.S. networks are using inches and their fractions (tenths and hundredths) to report precipitation. This explains uneven thresholds used throughout this paper. Classification of hourly rainfall by intensity by the U.S. National Weather Service observing handbook (USNWS 1994) assigns to hourly rates above 7.6 mm h\(^{-1}\) the highest rank of intensity. Keeping in mind that these rates (especially during the warm season) may occur within a few hours, we slightly raised this threshold for daily rainfall totals to those above 12.7 mm day\(^{-1}\) and in this paper focus only on these precipitation days and multiday events constructed from consecutive intense precipitation days. To be considered as one multiday intense precipitation event, all included days must be consecutive and each with precipitation above 12.7 mm.

Other definitions of precipitation intensity that we use are “moderately heavy” precipitation (within a 12.7–25.4 mm day\(^{-1}\) range), “heavy” precipitation (within 25.4–76.2 mm day\(^{-1}\) range), and “very heavy” precipitation (the daily rain events above 76.2 mm that for the Midwest correspond approximately to the upper 0.3% of the rain days; Groisman et al. 2004). We also define “extreme” daily and multiday rain events that may be
loosely attributed to floods, property damage, or even to human injuries and loss of life, as associated with precipitation totals above 154.9 mm.

Past research of changes in precipitation (and, in particular, intense precipitation) over the United States has found that total precipitation over the conterminous United States (CONUS) increased during the twentieth century by ~6% (Karl et al. 2009; NCDC 2010). These changes were not monotonic, nor were they spatially or seasonally homogeneous. During most of the twentieth century, moderately heavy and very heavy precipitation varied widely without apparent long-term trends, but in the past several decades the frequency of very heavy precipitation events began to increase over much of CONUS east of the Rockies, and their contribution to the annual totals also increased (Groisman et al. 2001; CCSP 2008). Specifically over the central United States (upper Mississippi, Midwest, and South; dark blue region in the inset map in Figs. 1 and 2), the changes in very heavy precipitation became statistically significant during the past 30–40 yr (Groisman et al. 2004, 2005). As a first step, we updated our daily precipitation time series up to the end of 2010 (Fig. 1) to verify that the last decades still show an increase in very heavy precipitation. We found that the only significant linear trends in the annual number of days with very heavy precipitation were located in the central United States. For consistency with Groisman et al. (2004, 2005) in the upper panel of Fig. 1 (and only there), we define very heavy precipitation as the upper 0.3% of daily precipitation events. The second panel in this figure shows the same time series, but very heavy precipitation was defined using fixed daily precipitation thresholds (equal to 76.2 and 101.6 mm day$^{-1}$) that we are using in this study. The threshold of 76.6 mm is close to the mean upper 0.3% of daily precipitation over the Midwest while 101.6 mm is close to the mean upper 0.3% of daily precipitation over the South region of the central United States. The conclusions about temporal changes in very heavy precipitation that can be drawn from analyses of these three time series are identical. Six linear trend estimates for three time series shown in this figure for the 1893–2010 and 1948–2010 periods are statistically significant at the 0.01 level or higher, and in the last 63 yr (1948–2010) the trend estimates are two to three times higher than for the entire 119-yr period. In other words, all systematic changes in very heavy precipitation frequency during the past 119 yr are ascribed to the 1948–2010 period. The follow-up inspection shows that the second half of this period is responsible for most of these changes.

In this paper we show what has happened with intense precipitation over the central United States during the past six decades and believe that the observed signal is too large to be unnoticed and deserves a thorough investigation. We are not alone in these concerns (cf. Hossain et al. 2009; DeAngelis et al. 2010).

2. Data

In the United States during the past 62 yr (1948–2009), the climatology of intense precipitation events, their regional distribution, internal structure (mean and peak hourly intensity and duration), and changes can be analyzed using the long-term time series of dense networks of daily and hourly precipitation gauges (Fig. 2). After a major data rescue effort in 2000, daily precipitation datasets (NCDC 2009) can be analyzed on a century time scale (cf. Groisman et al. 2001). Hourly
precipitation data (HPD), while these measurements have been conducted for more than 100 yr at a dense network of U.S. stations, are in digital form only for the 1948–2009 period (NCDC 2003).

Any analysis of temporal changes in the HPD data has to account for one important change at the network since the 1960s: from 1948 to 1960 all of the gauges were recorded with a resolution of 0.254 mm (0.01 in.). These gauges were gradually replaced so that currently more than 85% of HPD gauges record to a resolution of 2.54 mm (Fig. 3). Fortunately, this gradual replacement of gauges is well documented and we converted the data of the finer-resolution gauges to the uniform accuracy of 2.54 mm throughout the entire period of record. The conversion was made only to the recording gauges with hourly data reported up to 0.254 mm. Their records were allowed to mimic the gauge with course resolution by gradually accumulating small precipitation amounts until they reach 2.54 mm. Hours, when the accumulated value is less than 2.54 mm, are assigned a zero precipitation total. At the hour when the accumulated value, \( X \), reaches or exceeds 2.54 mm, it is reported as an hour with a nonzero precipitation equal to 2.54 \( [X/2.54] \) (where square brackets stand for entier). The residual amount \( (X - 2.54[X/2.54]) \) remains in the cache as it “stays” in the course-resolution gauge and participates in the accumulations in the next or in one of the following hours. This conversion is of critical importance. Without this adjustment for gauge resolution, an unaware user could generate grossly false conclusions about the changes in precipitation duration and intensity. The accuracy of the COOP network rain gauges has remained 0.254 mm throughout the entire period of observations.

Additionally, we employed in our analyses surface air and sea surface temperature archives (Lugina et al. 2003 and NCDC 2009 updated to 2010; and Smith et al. 2008 updated to 2009) and the ENSO statistics (CPC 2011) to evaluate possible relationships of the temporal changes of intense precipitation with regionally averaged surface air temperature over the central United States \( (T_{CUS}) \), contiguous United States \( (T_{CONUS}) \), Northern Hemisphere \( (T_{NH}) \), sea surface temperature over the Gulf of Mexico \( (T_{Gulf}) \), and El Niño–La Niña events.

3. Methodology

a. Data processing and analyses

We assessed climatology of the intense precipitation over the central United States at hourly, daily, and multiday time scales and have tracked its changes during the past 62 yr. Our intent has been to better understand
the nature of changes in the frequency of intense rainfall from daily and multiday events of consecutive intense rain days (up to the totals above 154.9 mm day\(^{-1}\)). The HPD network was used as the main data source, augmented by data from the COOP network. It is more difficult to work with HPD than with COOP data and, on average, during the study period we have in the central United States 2606 COOP versus 1291 HPD stations with data. However, the HPD network gives an opportunity to quantify mean and peak hour intensity and duration of intense precipitation and assess their changes with time (if any). The appendix contains a brief overview of our past efforts in studying intense precipitation over the contiguous United States and a rationale for terminology used.

At all stations, we selected only days (events) with intense precipitation (as defined above). We sorted these events and grouped them within seven intensity ranges. Thereafter, we summed all intense precipitation data within each daily or multiday intensity range, along with the correspondent peak hour intensity, number of days, and number of hours with nonzero precipitation during these days. From these tallies we calculated mean precipitation number of hours with nonzero precipitation during these correspondent peak hour intensity, number of days, and in each daily or multiday intensity range, along with the maximum hourly intensity for the days (events) with precipitation for each intensity category. The same approach was applied to subsets of data for:

- the first 31 yr and the last 31 yr of our sample,
- the warmest 31 yr and the coolest 31 yr during the 1948–2009 period using the mean annual surface air temperature of the Northern Hemisphere (\(T_{NH}\)), of the CONUS, of the central United States (\(T_{CUS}\)), and of the Gulf of Mexico (\(T_{Gulf}\)) as guidance;
- intense precipitation derived from tropical cyclones (TC) in the hurricane season (June–November) and intense precipitation that originated without direct TC impact;
- intense precipitation during various phases of the ENSO cycle (El Niño, neutral, and La Niña months); and
- various other combinations and complements—for example, warmest years versus coolest years for TC-originated precipitation and, separately for precipitation that was not originated from TCs, warmest years versus coolest years only for the hurricane-free season, warm season (May–October) temperatures for \(T_{CUS}\) and \(T_{Gulf}\), minimum and maximum temperatures for \(T_{CUS}\), etc.

b. Pro and contra of the present approach

1) FIXED THRESHOLDS VERSUS PERCENTILE-DEFINED THRESHOLDS

There are pro and contra reasons for selection of both types of thresholds. By selecting fixed thresholds for heavy precipitation of various intensities within a region, we initiate a preselection of locations where the micro-meteorological conditions induce these events to be more frequent. Examples are sites located on windward slopes versus the leeward slopes, coastal regions versus the inland sites, etc. In extreme cases (which are exactly a target of our assessment), we may unintentionally include only a few locations where extreme precipitation occurs because of a combination of orography and atmospheric circulation causes (e.g., Yakutat, Alaska). These results when regionally averaged do not represent the entire region but only its most humid areas. But, why is it worthwhile to look for extremes in the places where they do not (or are less likely to) occur?

Using the percentile thresholds that are crafted individually for each location, we (with an additional help of a carefully selected area-averaging procedure) receive a much better spatial representativeness for each region that accounts equally for precipitation extremes—for example, west and eastward of the Cascade Range in Washington State. The last example clearly identifies one of the problems of the percentile approach: it levels quantitatively disastrous and moderate precipitation events that may negatively impact hydrological estimates of consequences of intense rainfall over the rough terrain (even while the places that are used to huge precipitation events may have an infrastructure that is designed to take it). The second problem with the percentile approach, when we are looking for “real” extremes, is a low accuracy of individual threshold estimates at the far end of the tail of the empirical distribution. At the right-side tail, the ranked time series provide a broad range of neighboring values that may differ from each other by scores of millimeters. Thus, the estimated “threshold” carries with it both a peculiarity of the individual observing period at the site and a large random error of the estimate.

The discussion above hints that by bypassing the percentile estimates one can be better off by avoiding these two hidden caveats (leveling and low accuracy of the variables that are used only at an intermediate step of assessment). In the past, we experimented with and used both types of precipitation thresholds. With a clear understanding of the pros and cons of each, and having all the above considerations in mind, we selected fixed thresholds for this study.

2) PRESENT APPROACH VERSUS THE PREVIOUS METHOD OF PRESENTATION OF REGIONALLY AVERAGED RESULTS

In the past, we used an elaborate area-averaging routine that allowed us to account for unwanted impact of 1) station clustering and 2) missing values in the time series. These two factors could affect the regionally
averaged time series by introducing spurious trends (when the number of stations changed systematically) and/or introduce an imbalance in the regional average (when the cluster of stations in one part of the region unduly dominates the total number of stations available for analyses). In this study, we deliberately simplify the area averaging by analyzing the multidecadal total frequencies at all stations available at that period, omitting to account for possible clusters (in any case, the assessment based upon fixed thresholds does not allow for accurate regional representation of our extreme precipitation events frequency) and carefully accounting only for the average number of stations available during these periods in order to receive the accurate “per station” estimates. The last liberty was also justified by the period of our assessment (1948–2009) that was initially rich with data from well-developed HPD and COOP networks (cf. Fig. 2 and Groisman et al. 2001). We, however, tested our old and present methods of area averaging (not shown) to assure ourselves how our results were affected by the use of different area-averaging routines. For each network separately, they were not affected (see, however, section 4a below).

3) PRESENT APPROACH VERSUS EXTREME ANALYSES BASED ON ASSUMPTIONS ABOUT THE PRECIPITATION DISTRIBUTION AND/OR STATIONARY ERGODIC NATURE OF THE ONGOING CLIMATIC PROCESSES

There are a number of extreme analyses based on assumptions about precipitation distribution as well as about the distribution of “precipitation extremes” (cf. Zwiers and Kharin 1998; Groisman et al. 1999; Gershunov and Cayan 2003; Panorska et al. 2007; Zolina et al. 2009; Zhang et al. 2010; Beuger et al. 2011). Since 2003, a thorough effort to update a precipitation-frequency atlas of the United States [National Oceanic and Atmospheric Administration (NOAA) Atlas 14] is being conducted by the NOAA’s National Weather Service (http://www.nws.noaa.gov/ohd/hdsc/index.html). This effort, when it focuses on extreme precipitation, is also based upon assumptions about precipitation distribution and extreme value distributions (Bonnin et al. 2004a,b, 2006; Perica et al. 2009a,b). These assumptions are valid only for approximations or for very large samples. For example, 1) while gamma distribution is a good approximation of the form of precipitation distribution, attempts to derive this form from physical laws were not successful (cf. Bagrov 1965); and 2) Gumbel and generalized extreme value distributions are the limiting distributions for the maximum of a very large collection of independent random variables from the same arbitrary distribution (Coles 2001).

Furthermore, when the process becomes nonstationary (a very reasonable expectation now, when at least the global change is apparent) all these assumptions have to be reassessed. We are not alone in attempts to question these assumptions and this was done in most of the studies cited above when, for example, the selected parameters of extreme distribution were assumed to vary to account for the observed change (or to report its absence). But, relaxing the assumptions creates a new set of questions that are not easy to answer: why is a particular parameter assumed to be changing while others are not? Why use this form of the same distribution when the basic factors responsible for the precipitation process have changed or new factors (e.g., of anthropogenic origin) have been added? Stationarity of the process is “a single thing” but its changes can manifest themselves with different features. Therefore, in our present analysis we selected an approach that is completely free of assumptions and simply reports what has happened. After a better understanding of the causes of the observed change, more sophisticated assumptions (and analyses) can be brought into action.

4. Results

a. Climatology of intense precipitation over the central United States

Table 1 shows climatology of intense precipitation over three regions of the central United States (shown in Figs. 1 and 2) based upon HPD and COOP networks for the 1948–97 period. Comparison of results based upon two networks shows that the occurrence of days and events with intense precipitation (per station) are noticeably higher for the COOP network than for the HPD network particularly for very heavy and extreme precipitation. When averaging over the entire central United States, the differences are especially large. We calculated the average annual probability of extreme rain days at a single station by dividing the total number of these days during the 60-yr period by the mean number of stations in the region during this period and by 60 (yr). This probability at a single COOP (HPD) station in the 1948–2007 period was 0.027 (0.018). The same probability of observing a multiday extreme rain event with precipitation totals above 154.9 mm was 0.105 (COOP) and 0.073 (HPD). Two factors are responsible for these differences: 1) the COOP network is denser than the HPD network and 2) apparently a larger fraction of COOP stations are located in more humid areas (e.g., in the South; cf. Fig. 2). During the study period, COOP stations in the central United States received 17% more intense precipitation per station than the HPD
network (and 56% more extreme daily rainfall above 154.9 mm).

Analysis based upon HPD shows that peak hour intensity of precipitation remains relatively stable across the central United States for rain days and multiday rain events within the same daily/event totals ranges. However, it increases when these ranges go up, and on average in the extreme rain days peak hour intensity is six times higher than during the moderately heavy rain days.

Table 1 shows a strong meridional gradient in the frequency of intense precipitation across the central United States. In the upper Mississippi (Great Lakes), regional very heavy and extreme precipitation events are respectively four and seven times less frequent than in the South. However, when we assessed the temporal changes in each of these three regions, we found similarity of changes (in both signs and absolute values). Therefore, in the next subsection, we present in detail only our findings about the changes in intense precipitation for the entire central United States.

b. Temporal changes of intense precipitation over the central United States

Our analyses of temporal changes over the central United States show that a statistically significant redistribution in the spectra of intense precipitation days/events during the past decades has occurred. Moderately heavy events (that account for more than 70% of days and about half of intense precipitation totals) became less frequent compared to days and events with precipitation totals above 25.4 mm (Table 2). It might be instructive to compare this finding with that of Karl and Trenberth (2003). They sorted fractions of daily rainfall at the stations across the world with the same monthly totals by 10 mm day\(^{-2}\) categories for different temperature regimes (cold, warm, and hot). Their analysis showed that around the 30 ± 5 mm threshold, the
TABLE 2. Days with intense precipitation at ~1000 HPD (~2420 COOP) stations of the central United States during the first and second 31 yr of the 1948–2009 period presented separately for moderately intense precipitation events with daily precipitation totals, $P$, above 12.7 mm but less than or equal to 25.4 mm. The day count for the first 31 yr was scaled down by a factor of 0.95 (0.98) to equalize the mean numbers of HPD (COOP) stations during the first and the second half of the study period. Both $2 \times 2$ tables (cf. Kendall and Stuart 1979; continuity corrected asymptotic $\chi^2$ criterion) show that the fraction of “moderately intense” daily precipitation events was statistically significant decreasing with time.

<table>
<thead>
<tr>
<th>HPD network</th>
<th>Days with 12.7 mm</th>
<th>Last years</th>
<th>First years</th>
<th>All years</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; P \leq 25.4$ mm</td>
<td>423 576</td>
<td>429 012</td>
<td>852 588</td>
<td></td>
</tr>
<tr>
<td>$&gt; 25.4$ mm</td>
<td>593 996</td>
<td>584 393</td>
<td>1 178 389</td>
<td></td>
</tr>
<tr>
<td>All intense rain days</td>
<td>650.5</td>
<td>$P &lt; 0.001$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COOP network</th>
<th>Days with 12.7 mm</th>
<th>Last years</th>
<th>First years</th>
<th>All years</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; P \leq 25.4$ mm</td>
<td>1 197 922</td>
<td>1 166 027</td>
<td>2 363 949</td>
<td></td>
</tr>
<tr>
<td>$&gt; 25.4$ mm</td>
<td>520 036</td>
<td>468 910</td>
<td>988 946</td>
<td></td>
</tr>
<tr>
<td>All intense rain days</td>
<td>1 717 958</td>
<td>1 634 936</td>
<td>3 352 894</td>
<td></td>
</tr>
<tr>
<td>$X^2$</td>
<td>1018.3</td>
<td>$P &lt; 0.001$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

rainfall fractions are the same for each temperature range. However, for daily rainfall in other categories before and after this threshold, these fractions became systematically different. Using our terminology, in cold months, more frequent light and moderately heavy precipitation and less frequent heavy and very heavy precipitation are occurring than in warm and hot months. Moreover, the same pattern (and around the same threshold) is observed when daily precipitation distribution is compared between warm and hot months. Both analyses, ours and that of Karl and Trenberth (2003), put moderately heavy precipitation events apart from other intense precipitation events.

For different daily (multiday event) intensities, we calculated tallies of intense precipitation characteristics as described in section 3a for two 31-yr periods (1948–78 and 1979–2009). Figure 4 presents ratios (in percent) of these tallies for the past 31 yr to those for the previous 31-yr period. Prior to the comparison, we normalized the tallies (scaled them to per station values) to account for slightly different numbers of stations with data available for each 31-yr period. Figure 4 shows that during the past 31 yr (compared to the previous 31-yr period), significant increases occurred in the frequency of very heavy and extreme precipitation events in the central United States, with up to 40% increase in the frequency of days and multiday rain events with precipitation totals above 154.9 mm. The same test as in Table 2 was used to assure statistical significance of these increases. These changes imply a dramatic increase in these probabilities, causing a reduction of the return periods of precipitation extremes.

The internal precipitation structure such as mean and maximum hourly precipitation rates and precipitation duration (in hours) within each preselected range of daily or event totals did not noticeably change (cf. Fig. 5). This conclusion remained valid with all partitions (by time or by any other external factor that we employed). Results shown in Figs. 4 and 5 hint that while very heavy and extreme rain days and events became more frequent with time, the processes that control the internal structure of these events (e.g., peak hour rain intensity) do not change.

c. Role of tropical cyclones in observed changes of intense precipitation over the central United States

We used an algorithm described by Groisman et al. (2004) to assign the daily rain event as “associated to a tropical cyclone” or “TC related” and found that TC-related very heavy and extreme rainfall frequencies over the central United States during the hurricane season (defined as June–November in our analyses) changed between the two 31-yr periods similarly to other very heavy and extreme rainfall. In particular, the frequencies of the daily totals above 101.6 mm during the hurricane season changed with the same rates during TC and when we cannot associate extreme rainfall with a direct TC influence. However, all TC-related rainfall above 101.6 mm in the central United States reported at all of its HPD stations during the 1948–2007 period, ~1.1 mm yr$^{-1}$ per station, is a small fraction of all days with daily totals above 101.6 mm reported for the same period, ~1.46 mm yr$^{-1}$ per station (or 9.3 mm yr$^{-1}$ per station for the June–November “hurricane” season). The same comparison for TC-related rainfall above 154.9 mm gives 0.4 mm of TC-related rainfall versus 3.4 mm of the total rainfall accumulation per year per station. Thus, on average, TCs contribute only 11% of extreme rainfall over the region. This led us to the conclusion that extreme precipitation associated with TC does not significantly contribute to the changes shown in Fig. 4. This conclusion remains intact even for the southern “third” of the central United States (South region in Fig. 2). Since 1948 (actually, during the 1948–2007 period) among 856 rain days with rainfall above 154.9 mm at all HPD stations of the region (on average, 406 stations), we encountered 315 days during the no-hurricane season (December–May); 436 days during the June–November period that are not associated with tropical storms, depressions, or hurricanes; and 105 that
we named TC related. Thus, 88% of these extreme rain days were not TC-related and TCs were not a major factor responsible for temporal changes reported for intense precipitation even in its southernmost part.

d. Changes of intense precipitation over the central United States associated with temperature changes

For different daily (multiday event) intensities, we calculated tallies of intense precipitation characteristics as described in section 4a for two 31-yr groups of the years within the 1948–2009 period. Groups of years were selected to form the 31 warmest $T_{CUS}$ ($T_{CONUS}$, $T_{NH}$, and $T_{Gulf}$) years and compared them with the 31 coldest $T_{CUS}$ ($T_{CONUS}$, $T_{NH}$, and $T_{Gulf}$) years. If these factors impact the distribution of intense precipitation over the region, the comparison of two groups of years that are characterized by distinctively different values of these temperatures should reveal some features of this impact (if it exists). These four temperature characteristics changed differently during the 1948–2010 period. While $T_{CONUS}$ and $T_{NH}$ statistical significance increased during this period, with the rise of $T_{NH}$ being especially notable (linear trend describes 67% of the time series variance while, for comparison, only 9% of the annual $T_{CONUS}$ variance is described by linear trend), the other two temperature characteristics ($T_{CUS}$ and $T_{Gulf}$) did not increase.
show systematic one-directional changes. Below we present our estimates of changes in the intense precipitation distribution associated with these four temperature characteristics.

1) CHANGES OF INTENSE PRECIPITATION OVER THE CENTRAL UNITED STATES ASSOCIATED WITH SURFACE AIR TEMPERATURE CHANGES OVER ITS TERRITORY

Temperature changes over the region (and around it) may interact with precipitation affecting its intensity (in warmer weather conditions we can observe more intense precipitation) and be affected by precipitation. Climatology textbooks say (e.g., Geiger et al. 2003) that during the warm season, surface air temperature on rainy days is usually less than on no-rain days, and on clear-sky nights it is less than on rainy days; during the cold season, precipitation is usually accompanied by relatively warm surface air temperatures. Thus, in our analyses of changes of intense precipitation associated with regional surface air temperature changes, we selected two variables, $T_{\text{CONUS}}$ and $T_{\text{CUS}}$, and partitioned the years when these temperatures were especially warm (cold) annually and did the same for the warm season (May–October). In the warm season for $T_{\text{CUS}}$, we also checked the group partitioning based upon minimum and maximum (instead of daily) temperatures. While climatological considerations listed above are justifiable for point relationships between temperature and precipitation at the daytime scale, it was not known a priori that they remain valid when we compare large regional seasonal or annual temperatures with annual frequency of intense precipitation. Therefore, these relationships were checked. For each group pair and each of the three regions that compose the central United States in this study, we constructed ratios similar to those shown in Figs. 4 and 5. All these results for mean annual $T_{\text{CONUS}}$ and $T_{\text{CUS}}$ were found to be similar and did not reveal any notable changes in distribution of intense precipitation with corresponding changes in $T_{\text{CONUS}}$ and $T_{\text{CUS}}$ (not shown). For the warm season $T_{\text{CUS}}$, we found a negative association with all frequencies of intense precipitation that became more visible when we used the maximum $T_{\text{CUS}}$ temperature to partition the 1948–2009 period (Fig. 6). This finding probably does not require further discussion, but provides a mean regional quantification of the temperature–precipitation association in the warm season for the central United States; a 0.8°C (1.1°C) increase in mean (maximum) $T_{\text{CUS}}$ is associated with a 10%–20% decrease across all ranges of intense precipitation (except extreme rainfall). It should also be noted that during this 62-yr period there were no systematic changes in the annual and warm season mean daily and minimum $T_{\text{CUS}}$. However, May–October maximum $T_{\text{CUS}}$ has decreased [by 0.9°C (62 yr)$^{-1}$] with the lowest value in 2009, which is statistically significant. The seasonal maximum temperature difference between the first and second 31-yr periods is $-0.37^\circ$C. Thus, a fraction of observed temporal increase in intense precipitation over the central United States can be associated with a decrease of the warm season maximum temperature over the region. It may well be that the maximum temperature decrease was caused by wetter warm seasons in the last decades rather than an opposite inference (cf. also Changnon 2010).

2) CHANGES OF INTENSE PRECIPITATION OVER THE CENTRAL UNITED STATES ASSOCIATED WITH SURFACE AIR TEMPERATURE CHANGES OVER THE NORTHERN HEMISPHERE

Analyses of the changes in precipitation intensity over the central United States in a “global warming experiment” (for which we specifically selected the 31 warmest $T_{\text{NH}}$ years and compared them with the 31 coldest $T_{\text{NH}}$ years), closely resemble the results reported in section 4b for its temporal changes over the central United States. Figure 7a shows why this happens. Only a few years in the “cold” group (3) are from the last three decades (after 1979) and grouping by time and by $T_{\text{NH}}$...
are highly correlated. Three other panels of Fig. 7 provide the results of comparison (similar to what is shown in the upper-left panel of Fig. 4), but these are for each of three regions that compose the central U.S. domain and for the group partition using annual $T_{NH}$ as guidance. These three panels as well as their composition for the central United States (not shown) illustrate the fact that with an increase of the hemispheric temperature the intense precipitation distribution is changing; the frequency of moderately heavy precipitation events does not change but very heavy and extreme precipitation events became more frequent. The disproportionally high number of changes of extreme events over the northernmost region of the upper-Mississippi and Great Lakes area can be explained by their very rare occurrence there. During the entire 62-yr period at ~230 HPD stations in this region, only 62 days with rainfall above 154.9 mm were reported. For comparison, in the Midwest 175 of these events at ~370 HPD stations and in the south 886 of these events at ~400 HPD stations were reported during the same 62-yr period. Of course in this situation one extreme event at a cluster of stations in the upper-Mississippi and Great Lakes area could disproportionally tip our counts for this region, but for the entire central United States with more than 1100 of such daily events (as reported on average by ~1000 stations at the HPD network) and/or 4150 daily extreme events (as reported on average by ~2420 stations at the COOP network) the conclusions about observed changes became more stable and trustworthy.

3) CHANGES OF INTENSE PRECIPITATION OVER THE CENTRAL UNITED STATES ASSOCIATED WITH SEA SURFACE TEMPERATURE CHANGES OVER THE GULF OF MEXICO

Southward of the central United States resides a significant source of water vapor for the atmosphere above the region: the Gulf of Mexico. Studies of the water vapor sources for precipitation over the Mississippi River basin conducted during the first Global Energy and Water Cycle Experiment (GEWEX) continental experiment show that, while the quantitative estimates varied widely, most precipitation over the central United States originated from external moisture sources (e.g., Brubaker et al. 1993; Trenberth 1999). The Gulf of Mexico is among primary candidates for origination of these sources.
Therefore, it was considered instructive to examine whether the frequencies of intense precipitation over this region can be traced to temperature anomalies in the Gulf. We selected monthly sea surface temperatures area averaged over the sector (18°–30°N, 100°–80°W), excluding land areas and two grid cells off the Florida’s oceanic coast. Partitioning into two 31-yr groups was made as described in section 3a using as guidance the annual $T_{\text{Gulf}}$ and (separately) the May–October $T_{\text{Gulf}}$. Neither of these temperature time series had linear trends during the study period. Figure 8 shows the results of this analysis when we used as guidance the annual $T_{\text{Gulf}}$. The warmer $T_{\text{Gulf}}$ (annual sea surface temperature difference between the two periods was 0.27°C) period is associated with less intense precipitation over the central United States for all intensity categories, which constitute more than 70% of annual precipitation totals. Moreover, while for moderately heavy and heavy precipitation, the decrease varies in the range of 3%–7% and for daily precipitation above 76.2 mm the decrease varies from 10%–20%, rising gradually for higher rainfall range categories.

It is difficult to expect that precipitation over the central United States may significantly affect $T_{\text{Gulf}}$ (more Mississippi streamflow?), but the opposite is easier to assume. Warmer Gulf temperatures may mean more evaporation that, with appropriate southern winds, can bring more precipitation to the central United States. However, we observe an opposite sign of the intense precipitation changes with $T_{\text{Gulf}}$. Furthermore, when we repeat our analysis with grouping that uses as guidance the warm season $T_{\text{Gulf}}$, we found no signal; the ratios between two groups in each category of intense precipitation were close to 1. This means that the possible $T_{\text{Gulf}}$ impact on the intense precipitation distribution that has a natural peak in the warm season 1) may be provided by the sea surface temperatures in the cold season months or 2) is not related to its warmer temperatures but rather is related to the atmospheric dynamic conditions associated with warm Gulf waters. Warmer temperatures in the Gulf of Mexico were documented with a low phase of the ENSO—that is, in the La Niña periods (Halpert and Ropelewski 1992). Our analyses using sea surface temperature and ENSO indices available from the Climate Prediction Center (CPC 2011) show that during the 1948–2009 period the Gulf warm season temperature was 0.15°C warmer in the El Niño months than during the La Niña months, but during the cold season (November–April) this difference was −0.1°C (the annual temperature difference remains +0.2°C). It is reasonable to expect that to explain why in Fig. 8 with warmer annual $T_{\text{Gulf}}$ we observe less intense precipitation, we need to look further into the ENSO–precipitation relationships. These relationships are well studied (cf. Ropelewski and Halpert 1986, 1987) and, while they are generally beyond the focus of this paper, they are assessed separately in the next subsection.

e. Changes of intense precipitation over the central United States associated with ENSO phases

During the 1948–2009 period using the data source CPC (2011) and supplementary information about the ENSO in the late 1940s, we selected two groups of months (each of 178 months) with El Niño and La Niña. While doing this, we had to slightly trim the La Niña sample in 1949–54 in order to match the number of months identified with El Niño conditions (the total number of months with La Niña was 199). However, during the past three decades there were 105 months with El Niño and only 71 months with La Niña. This change is well known (CPC 2011), is in line with projected “El Niño–like” changes during the global warming (Solomon et al. 2007; CCSP 2008), and can be a potential cause of systematic changes. Therefore, in Fig. 9 we assess the differences between El Niño, neutral, and La Niña months in the intense precipitation over the central United States. It is worth repeating here that very heavy precipitation above 101.6 mm represents only 0.14% of all nonzero daily precipitation events and 2% of totals over the region (cf. Table 1 and the first paragraph of section 1). Thus, the upper panel of Fig. 9 shows that the majority of intense precipitation events except those above 101.6 mm (and above 76.2 mm in the upper-Mississippi subregion; not shown) are nearly similarly frequent over the central United States during the El Niño and La Niña months. This similarity (and close values of regional precipitation totals during the El Niño and La Niña months) explains why past analyses (e.g., Ropelewski and Halpert 1986) did not identify these regions (except the Gulf coast) as affected by ENSO. However, the situation became very
different for very heavy precipitation above 101.6 mm (above 76.2 mm for the upper-Mississippi subregion). A 20% or more difference indicates that El Niño months are associated with substantially more frequent very heavy rainfall than La Niña months. For extreme rainfall (above 154.9 mm) we observe only 10% more frequent rain days, hours, and rainfall in the El Niño than in the La Niña months. With La Niña, hurricanes hit the U.S. coast more frequently (Stooksbury 2003). It is possible that their less-frequent landfalls in the El Niño months somewhat reduce (but do not eliminate) an increase in extreme rainfall events over the central United States in the El Niño months compared to the La Niña months.

Together, El Niño and La Niña months constitute about 51% of all months in the 1948–2009 period; 27% of these months were La Niña and 24% El Niño conditions. In the second half of this period, 28% of months were El Niño and 19% La Niña conditions, together constituting about 47% of all months in the 1979–2009 period. This means that the relationship shown in the upper panel of Fig. 9 hides inside itself a temporal component; El Niño and La Niña months are not randomly distributed with time. It looks like ENSO is affecting the intense precipitation distribution over the central United States, and the event itself changes with time; an increase in the El Niño frequency and reduction in the La Niña frequency are collinear with the global warming process in the last decades. To eliminate the impact of interdecadal differences in months selected, three additional grouping experiments were conducted.

We compared 1) neutral ENSO months versus all other months (with El Niño and La Niña), 2) neutral ENSO months versus El Niño months, and 3) neutral ENSO months versus La Niña months. In these experiments we selected a shorter 1958–2009 time period when all three groups of events occurred approximately “in the same time intervals” (i.e., the events were more equally distributed with time, and the average dates of occurrence for each of three types of events were close). By doing this, we eliminated the temporal component from the studied inferences that 1) do exist (cf. section 4b) and 2) strongly affected some of our relationships (e.g., with $T_{NH}$). Because neutral ENSO months are about half of the entire 52-yr period (the number of months in each group was different: 313, 164, and 147 months for neutral, El Niño, and La Niña events, respectively), we used appropriate scale factors applied during the comparisons. For example, to construct the bottom panel of Fig. 9, the ratios of neutral and La Niña intense precipitation totals, days, and hours were multiplied by 147/313. Generally speaking, mean monthly intense precipitation totals and frequencies over the central United States for each phase of the ENSO cycle are quite close with those during the neutral phase months, being about 5% less than for La Niña and El Niño months. The intensity frequency spectra of intense precipitation in the El Niño and neutral months are similar and the empirical probabilities of the frequency of extreme rain events nearly coincide. However, this spectra distribution became different in the La Niña months (Fig. 9, bottom panel).

This panel shows that in the neutral years (even while the intense precipitation totals are below average) very heavy and extreme precipitation are notably (up to 20%) higher than in the La Niña months. Taking into account a similar result shown in the upper panel of this figure and elimination of the “temporal factor” from this set of experiments, we conclude that 1) La Niña conditions are associated with a smaller number of very heavy and extreme precipitation events over the central

![Fig. 9.](http://journals.ametsoc.org/doi/abs/10.1175/2011JHM1377.1)

- **Top Panel**: Comparison of intense precipitation days over the central United States for two equal 178-month periods with El Niño and La Niña conditions sorted by daily intensities (mm). Estimates of precipitation characteristics for these 178-month periods were averaged and their ratios (El Niño to La Niña, in % per station) are shown for HPD network.
- **Bottom Panel**: Same at (top) but for months with neutral and La Niña conditions during the 1958–2009 period sorted by daily intensities (mm). Estimates of precipitation characteristics for these 313- and 147-month periods were averaged and their ratios (neutral to La Niña, in % per station per month) are shown for HPD network.
United States than other ENSO phases and 2) because these conditions became less frequent in the past decades, this aspect of the global climatic change development can contribute to the observed increase of the occurrence of very heavy and extreme precipitation over the study region.

f. Summary of results

A brief summary of the above findings are as follows:

- we constructed regional climatology of intense precipitation over the central United States based on in situ data and showed how it depends upon the network selection;
- we found that in the past three decades the frequency of intense precipitation days and events with totals above 25.4 mm has increased while more numerous moderately heavy rain events (with totals in the range from 12.7 to 25.4 mm) did not change—the change in the frequency of extreme rain days (events) with totals above 154.9 mm was the most pronounced (a 40% increase);
- these changes are collinear to those associated with changes in the mean annual temperature over the Northern Hemisphere;
- we found that rainfall from tropical cyclones did not play a key role in the above changes;
- we found that while very heavy and extreme rain days and events became more frequent with time, the processes that control the internal structure of these events (e.g., duration and peak hour rain intensity) do not change;
- we found inverse relationships between intense precipitation over the central United States and 1) regional warm season T_{max} and 2) the annual Gulf of Mexico temperature; and finally
- we found an inverse relationship between very heavy and extreme precipitation days over the central United States and La Niña conditions.

5. Discussion

In this section we discuss possible causes of the observed temporal changes in intense precipitation distribution, possible implications of these changes, and outline pathways to potential users of climatic change information how to use our findings.

a. Possible causes of the observed temporal changes in intense precipitation distribution over the central United States

Figure 4 shows that substantial changes in intense precipitation with daily totals above 25.4 mm have occurred over the central United States during the past several decades. Here, the changes occur simultaneously with changes in several other water cycle characteristics such as increases in prolonged no-rain periods (Groisman and Knight 2008) and minimum streamflow (Lins and Slack 1999). But why do they occur? Below we discuss several potential causes of observed changes in intense precipitation. We are doing this without firm conclusions that may require further studies, especially because several collinearly occurring factors can contribute more or less to observed changes in intense precipitation over the study region.

1) CAUSES ASSOCIATED WITH GLOBAL CHANGES

The 1979–2009 period is characterized by approximately 0.5°C warmer T_{NH} than the previous decades (0.55°C according to Lugina et al. 2003, updated). At the same time, the number and duration of the El Niño events substantially increased compared to the previous three decades (105 versus 73 months) and the duration of the La Niña events has decreased (71 versus 128 months). Our results indicate that both of these global factors (T_{NH} and La Niña) influenced the distribution of the intense precipitation over the central United States. Keeping in mind that paleoclimatic reconstructions and the contemporary climate models support some level of relationship between the global warming process and the ENSO behavior (Wara et al. 2005; Latif and Keenlyside 2009; Kug et al. 2011), it would be tempting therefore to associate the observed changes in intense precipitation over the central United States to the global climate change. If true, this would have disastrous implications. If a 0.55°C increase was accompanied by a 40% increase in extreme precipitation, what can we expect from global temperature increases projected for the next few decades? Would it be possible to mitigate this unfortunate scenario? However, we believe that this would be a hasty conclusion (cf. the next two subsections).

2) CAUSES ASSOCIATED WITH REGIONAL CHANGES BEYOND THE REGIONAL BOUNDARIES

The size of our study area (about 20° latitude × 20° longitude) and a similarity of changes in intense precipitation distribution across the three subregions of the central United States hint that the observed changes cannot be attributed to the latitudinal shift in storm tracks guided by the westerlies across the region. It can be assumed though that the meridional transport of moisture from the south (e.g., from the Gulf of Mexico) can control these changes. Our analysis [sections 4d(3) and 4e] does not exclude this possibility but shows that
while there is relationship between sea surface temperatures in the Gulf and intense precipitation distribution over the central United States, its causes cannot be considered regional but most probably are related to a global factor: ENSO. Moreover, there are no statistically significant trends in $T_{\text{Gulf}}$, which makes this variable an unlikely candidate to control the observed systematic changes in intense precipitation over the central United States.

DeAngelis et al. (2010) assessed the potential impact of increasing irrigation in the high Great Plains (the Ogallala Aquifer) on the summer precipitation over the central United States. Analyses of the literature, process studies, modeling experiments, water vapor tracking within the regional reanalyses and climatic models’ output made a strong case that the anthropogenic increase in evapotranspiration (ET) over the Great Plains under irrigation (just westward of the central United States) can lead to an increase in summer rainfall. In support of these theoretical projections, they found a 20% statistically significant increase in observed July precipitation over the region located in the center of our study area (~Midwest) for the 1950–2000 period compared to the previous 50 yr. Our results cannot be directly compared to those of DeAngelis et al. (2010). Different regions, different variables, different time scales, different potential causes, and different periods were assessed in our two studies. However, both studies share a concern that human activity in the central United States and the adjacent areas can interact and change various components of the regional water budget. Our considerations on this matter are presented in the next subsection.

3) CAUSES ASSOCIATED WITH REGIONAL CHANGES MOSTLY WITHIN THE REGION (REGIONAL TEMPERATURE, RESERVOIRS’ STORAGE, AND AGRICULTURE STRUCTURE AND PRODUCTIVITY)

In section 4d(1), we showed a relationship between regional maximum warm season temperature ($T_{\text{max}}$) and distribution of the intense precipitation; they are negatively correlated and $T_{\text{max}}$ has a negative trend during the 1948–2010 period. However, even if we assume that its changes are responsible for observed changes in regional rainfall, the $T_{\text{max}}$ decrease between the two 31-yr periods is 1) insufficient to describe the observed changes in intense precipitation distribution and 2) does not explain all the observed change in extreme rainfall in the past three decades. It is most probable (this suggestion also requires support by regional climate model calculations instead of a bold statement) that an impact in the opposite direction was observed; more frequent intense precipitation caused the $T_{\text{max}}$ decrease.

In the central United States, the water cycle changes observed over the past 70 yr have occurred simultaneously with changes in land use and water management (USGS 2004). Large reservoirs may significantly alter local precipitation patterns by increasing the probability of extreme rainfall as the result of intensification of the hydrological cycle through enhanced evaporation from open-water bodies (Eltahir and Bras 1996). Registered dams in the United States (~75 000 of them) are capable of storing a volume of water equaling almost one year’s mean runoff of the entire nation (Graf 1999). According to the National Inventory of Dams, most of them (~40 000) were built from the mid-1940s to the end of the 1970s—many of them in the central United States—whereas another ~20 000 were built prior to 1945. For example, the area of large reservoirs in Illinois during the 1979–2009 period doubled compared to the previous 31 yr.

In the past several decades there have been major changes in agricultural management practices in the central United States. Among these are a near quadrupling of plant density for maize, adoption of soybean as a major crop essentially producing a biculture (corn and soybean) managed ecosystem, and earlier planting dates as a result of advances in mechanization and plant breeding (Swanson and Nyankori 1979; O’Neal et al. 2005). Intensification of agriculture and changing crop patterns over large areas of the central United States (including the upper Great Plains) consumes (and transpires back into the atmosphere) a significant amount of additional water requiring tapping groundwater storage and intercepting and diverting runoff. Therefore, changing crop patterns and water use over large areas may feed back to the water cycle through changes in transpiration and evaporation from additional open water surfaces, thus supplying the atmosphere with additional water vapor. These feedbacks became stronger in the last decades compared to the 1948–78 period when dams were under construction and many agriculture intensification measures were still in the planning stage. In Table 3 and Fig. 10, we put together a few crop statistics for the Corn Belt states that illustrate the above statements. While a quantitative assessment of the land and water use dynamics over the entire central United States goes well beyond the scope of this paper, Fig. 10 illustrates our above arguments. More than doubled total corn and soybean yield in three major producer states (Iowa, Illinois, and Indiana; tripled for Iowa soybeans) requires for its production additional water, part of which transpires to the atmosphere. A brief check of the wheat yield in the central states of the United States...
shows that the water consumption (and thus the transpiration) here has also increased. For example, total wheat yield has increased by 50% in Kansas, Missouri, and Oklahoma without significant changes in total field areas. In Illinois, we observe a 15% increase of the wheat yield from the fields whose area in past three decades has become 25% less than in the three post-WWII decades.

The local land and water use factors mentioned above may change the precipitation recycling ratio. The regional changes in intensity of the water cycle are usually quantified through the precipitation recycling ratio that describes the contribution of local evaporation to local precipitation (Eltahir and Bras 1996). Estimates made under the GEWEX continental-scale experiment in the Mississippi River basin showed that recycled precipitation plays a significant role during the warm season (Brubaker et al. 1993) and vary depending on definitions and estimation methods. Trenberth (1999) estimates the annual recycling ratio for the Mississippi River basin at 21%, and Bosilovich and Schubert (2001) reported a large interannual variability of this ratio between dry and wet summers. Zangvil et al. (2004) pointed to an interrelationship between agriculture production and precipitation recycling in the region. All of the above show that rainfall recycling is a significant local source of precipitation especially in the warm season and indicates a potential for strong feedbacks of the land use and water management changes to the hydrometeorological conditions over the central United States. Therefore, any external impact on water recycling (e.g., anthropogenic) can substantially change the entire regional water budget and precipitation intensity distribution (cf. Stidd 1975; Avissar and Liu 1996; Sacks et al. 2008; Feddema et al. 2005; Mahmood et al. 2010).

### Table 3. Harvested area (km²) and total yield (bushels × 10⁶) of corn for grain and soybeans in the Corn Belt U.S. states during the 1948–78 and 1979–2009 periods. Data source used to create the table is NASS (2010). In the last decades, corn and soybean fields in the three Midwestern states—Indiana, Illinois, and Iowa—occupied 47%, 58%, and 61% of the states’ land area, respectively. The table does not provide area of corn planted for silage because the appropriate statistics are available to us only since 1972. However, the areas of these fields are small (e.g., on average, 1.5%–3% of the area occupied by cornfields in Illinois and Iowa, respectively).

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* For the previous 19 yr only (instead of 31 yr).

### b. Possible implications of the observed temporal changes in intense precipitation distribution

#### 1) IMPLICATIONS FOR THE PRESENT CLIMATIC AND ENVIRONMENTAL ASSESSMENTS

Observed temporal changes in intense precipitation distribution up to present (Figs. 1 and 4 were updated to 2010 and 2009, respectively) raise an urgency of the up-to-date routinely reassessed meteorological information on precipitation intensity (cf. Bonnin et al. 2004a,b, 2006; Perica et al. 2009a,b; Table 1). Not everything is changing and not everywhere are the changes visible beyond the level of “weather noise.” However, the variables that we looked at over the central United States, in particular very heavy and extreme precipitation, have changed significantly and their dynamics require attention from hydrologists and other consumers of this type of precipitation information.

Climatologists who employ methodologies based upon stationary stochastic processes need to reconsider...
their approaches. Appropriate methods are already available (cf. Zhang et al. 2010; Panorska et al. 2007).

Traditional trend analyses may require caution when applied to insufficiently long periods of time. For example, the last three decades are a period for which the international climatological community has performed most of its global and continental precipitation data analyses (cf. the Global Precipitation Climate Project and the North American Regional Reanalysis). It is worthwhile to note that for these analyses (at least in the central United States) we have a very different precipitation spectra compared to the previous years. Therefore, for example, the trend analyses within this period alone may mislead and require special interpretation.

Climate modelers are keenly interested in the past century observations that allow them to quantify and support the sensitivity of their precipitation schemes (particularly for convective rainfall) to contemporary climate variability and changes. Several years ago, the model output by Semenov and Bengtsson (2002) for the northeastern quadrant of CONUS supported our results on the changes in heavy precipitation and inspired us to reproduce their findings for the no-rain periods frequency (Groisman et al. 2001, 2005; Groisman and Knight 2008). Similarly, we expect that climate modelers may be interested to check the performance of their models for the central U.S. intense precipitation dynamics.

Specialists in remote sensing have difficulties in calibrating their present and projected nearly instant precipitation observations versus available in situ information. Various models that include wind, humidity, and cloudiness information are used for conversion of these remote sensing products into reliable precipitation totals (Levizzani et al. 2007; Mikaelidis 2008; Gebremichael and Hossain 2010). Additional constraints (e.g., those in Fig. 5) and the information about changes in precipitation intensity distribution (e.g., those shown in Figs. 4, 7, and 9) and future accounting for the land use change impact on rainfall [hypothesized in section 5a(3)] may assist in making these models more accurate.

Physicists who study the precipitation process formation may be interested in the results shown in Fig. 5. We show that peak precipitation intensity and duration are functions of daily and multiday precipitation totals being broadly similar within fixed precipitation ranges (Table 1). Figure 5 and many graphs similar to it (not shown in the paper) illustrate the stability (invariant) of these internal precipitation process characteristics with temporal and various climatic perturbations within each subregion of the central United States. The last matter is also of importance for soil erosion modeling and therefore represents a particular interest for agronomists (cf. SWCS 2003).

Hydrologists and civil engineers whose major concern is the regional water budget may not be interested in changes of a relatively small fraction of precipitation totals reported above (let us remember that the most frequent moderately heavy precipitation events practically did not change in our data partition experiments). However, those whose concern is the frequency of very heavy and extreme precipitation events (e.g., for disaster control management) may take notice of the observed changes reported in this paper. This information may help them to better operate in the present, already changed climatic conditions (i.e., to know the contemporary climatology of the extreme rain event frequency).

**FIG. 10.** (top) U.S. Corn Belt states with the areas (% of total land area) occupied by corn (red) and soybean (blue) fields in the last three decades. A core region where more than half of land area is occupied by corn and soybeans is outlined by dashed oval line. Dark green shows dense production, and light green less production but still important (Hart 1986). (bottom) Changes between 1979–2009 and 1948–78 periods, showing increase (by %, compared to the previous 31 yr) in area of harvested corn for grain (red) and soybeans (blue) and in total yield of corn (red) and soybeans (blue). Data source used to create the table is NASS (2010).
and begin preparations for the future (cf. next subsection).

2) IMPLICATIONS FOR PROJECTIONS OF THE FUTURE

There are good reasons to expect that some of the observed changes in intense precipitation over the extratropical land areas (including the central United States) are a part of the global climatic change (Figs. 7 and 9; Solomon et al. 2007; CCSP 2008). However, in parallel, there were large-scale land use changes over the central United States [Fig. 10; section 5a(3)] and its adjacent areas (DeAngelis et al. 2010; Vogel et al. 2011) that could also shift the regional water budget in the same direction. Over the next several decades society cannot realistically impact the global climate component of earth system changes. However, the impact of regional land use changes (after it is understood and quantified) arguably can be projected and even reversed if its negative impact is proven. We have observed large changes in extreme rainfall over the central United States. More comprehensive studies will be required to perform a special study to separate climatic and local anthropogenic factors in any attribution of causality. A combination of global and regional climate and hydrological modeling driven by well-documented external anthropogenic forcing (that includes, in addition to global factors, regional land use and water management changes) can be a way to perform this attribution study. It is easy to envision (but extremely laborious to do) a suite of experiments with high-resolution GCMs coupled with regional climate, hydrological, and agrometeorological models focused on the central United States and driven 1) solely by external global forcing (greenhouse gases, aerosol, solar, etc.) and 2) by the same combination of the external global forcing factors and known regional land surface changes during the past 60–70 yr. The differences between two groups of model runs may provide insight to the regional changes (including those shown in Fig. 4) which have occurred and, possibly, how the detrimental component of regional factors (we assume that there is some control of the anthropogenic component of these factors) can be mitigated.

6. Conclusions

Intense precipitation (with daily totals above 12.7 mm) contributes about 70% of precipitation over the central United States during approximately 25% of all rainy days. Within the intense precipitation spectra we distinguished days and events with moderately heavy (12.7–25.4 mm), heavy (25.4–76.2 mm), very heavy (above 76.2 mm), and extreme precipitation (above 154.9 mm). Within these four groups of intense precipitation, 49.9%, 43.2%, 6.9%, and 0.7% totals are falling in 72.3%, 26.0%, 1.7%, and 0.1% of days with intense precipitation during 61.3%, 35.2%, 3.5%, and 0.2% of hours with precipitation, respectively (as reported at the HPD network). Using the COOP network these numbers are slightly different. Daily totals of intense precipitation is partitioned among these four groups as 47.4%, 44.7%, 7.9%, and 0.9% that fall in 70.5%, 27.5%, 1.9%, and 0.1% of days with intense precipitation, respectively.

We found substantial changes in heavy, very heavy, and extreme precipitation over the central United States during the past several decades (10%–40% increase with a 40% increase in the frequency of daily rain events above 154.9 mm) but no changes in the moderately heavy precipitation events. This leads to a redistribution of intense precipitation across its intensity distribution spectra.

The 1979–2009 period is characterized by approximately 0.5°C warmer $T_{\text{NH}}$ than the previous three decades. At the same time there was a substantially increased duration of the El Niño events at the expense of La Niña events. We showed that both these global factors can be responsible (completely or partially) for the observed increase in intense precipitation over the central United States with the changes associated with the increase in hemispheric temperatures being most congruent to the observed change.

Regional maximum temperature in the warm season ($T_{\text{max}}$) has decreased during the 1979–2009 period compared to the previous decades. This regional decrease in $T_{\text{max}}$ may be considered as a possible consequence of the observed increase in intense precipitation and land use change.

Significant intensification of land use and water management in the central United States and in its adjacent regions (Table 3; Fig. 10; Changnon 2010; DeAngelis et al. 2010) during the past decades should lead to an additional regional water vapor source over the central United States in the warm season. While we cannot quantify its contribution to the observed changes in intense precipitation without using agrometeorological and regional climate modeling, we believe that our analyses have made a strong case for the need of such effort.

Over the next several decades, society cannot realistically impact the global climate component of earth system changes. However, the impact of regional land use changes (after it is understood and quantified) arguably can be projected and even reversed if its negative impact is proven and outweighs its benefits. A combination...
of global and regional climate and hydrological modeling driven by well-documented external anthropogenic forcing (that includes, in addition to global factors, regional land use and water management changes) can be a way to perform this attribution study. Only thereafter can the acquired knowledge be used for realistic regional projections of intense precipitation including extreme rainfall.

Changing extreme rainfall (regardless of cause) creates new challenges to those civil engineers who handle the consequences of extreme precipitation events. Assumptions presently being used may already be invalid and definitions (e.g., 100-yr flood, etc.) need to be reassessed to accommodate the changing climate conditions. This reassessment cannot be a one-way street and a closer collaboration is warranted between these civil engineers and the scientists who document and project climatic changes.

**Acknowledgments.** NOAA Climate Program Office provided support to this study. Thoughtful recommendations of three anonymous reviewers helped us to significantly improve the manuscript.

**APPENDIX**

**Research Defined by Advances in Data Availability**

During the past 12 years, we studied changes in intense precipitation over the contiguous United States from different perspectives and using different methods and databases (Karl and Knight 1998; Easterling et al. 2000; Groisman et al. 1999, 2001, 2004, 2005; CCSP 2008). The common feature in these datasets was the aggregation of precipitation to daily totals because, initially, there were no other reliable sources of climatological information on precipitation changes. The U.S. Historical Climatology Network, which included initially 182 stations with daily data (now more than 1200 stations; http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html), was used by Karl and Knight (1998), Groisman et al. (1999), and Easterling et al. (2000) to assess the upper-fifth percentile of stations’ daily totals, the number of days with precipitation above 50.8 mm, and the changes in parameters of precipitation distribution with time. When the major archive of daily COOP stations was updated backward from 1948, we were able to employ about 6000 daily time series over the United States and assess the century-long changes in very heavy precipitation events (cf. Groisman et al. 2004, 2005; CCSP 2008). At each step, our advance was defined by new digital datasets of scientific quality that became available at that time and societal demand fuelled by accelerated climatic changes and GCM projections. The term “extremes” was and sometimes is overused. Values at the tail of the probability distribution technically qualify to be considered as extremes. However, there is no common agreement as to how far from the center of this distribution the extremes lie. The definition of extreme may well depend on the scientific, social, political, engineering, etc. application in order to evaluate the size of the extreme we are looking for. Upper 5% of daily events, maximum annual value, etc. were frequently used in theoretical climatological assessments (e.g., Solomon et al. 2007), but in other areas (e.g., in hydrology, in civil engineering, and in studying natural and anthropogenic hazards) the term extremes has a negative connotation. It is more widely used to describe situations that cause damage that must be prevented, mitigated, and/or accounted for in long-term planning such as construction of houses, bridges, other infrastructure, human health protection, and water management. In our opinion, the upper 5% of daily precipitation events (that across the conterminous United States on average occur 20 times per year and bring about 30% of annual precipitation totals) and/or a mean peak annual precipitation event do not qualify for the definition of extremes. That is why 10 years ago we began using more neutral terminology—heavy, very heavy, and intense precipitation (cf. Groisman et al. 2001, 2005). The current concern is the possible changes in real extremes (i.e., those that do endanger human life and/or well-being). These extremes are associated with very rare precipitation events. For example, days with rainfall totals above 154.9 mm over the HPD stations of the contiguous United States occurred once per 60 yr over the Midwest, once per 135 yr, etc. It was expected that an attempt to analyze these rare events from observational data is challenging, requires redesigning the approach, and, nevertheless, may deliver results with a lesser confidence than those for 0.3% percentiles. Using a second independent precipitation dataset (HPD) and using the data only after World War II (which are much more numerous), we went ahead and in section 3 outline our methodology as well as the rationale of the differences in approach used here and in our previous studies (cf. Groisman et al. 2004, 2005).

**REFERENCES**


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