Heavy Precipitation and High Streamflow in the Contiguous United States: Trends in the Twentieth Century

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ABSTRACT

Changes in several components of the hydrological cycle over the contiguous United States have been documented during the twentieth century: an increase of precipitation, especially heavy and very heavy precipitation, and a significant retreat in spring snow cover extent over western regions during the last few decades.

These changes have affected streamflow, including the probability of high flow.

In the eastern half of the United States a significant relationship is found between the frequency of heavy precipitation and high streamflow events both annually and during the months of maximum streamflow. Two factors contributed to finding such a relation: 1) the relatively small contribution of snowmelt to heavy runoff in the eastern United States (compared to the west), and 2) the presence of a sufficiently dense network of streamflow and precipitation gauges available for analysis. An increase of spring heavy precipitation events over the eastern United States indicates with high probability that during the twentieth century an increase of high streamflow conditions has also occurred. In the West, a statistically significant reduction of snow cover extent has complicated the relation between heavy precipitation and streamflow. Increases in peak streamflow have not been observed here, despite increases in heavy precipitation events, and less extensive snow cover is the likely cause.

1. Background

Significant changes in precipitation, evaporation, and snow cover extent have occurred over the contiguous United States during the past 50 years (Groisman and Easterling 1994; Karl and Knight 1998; Kunkel et al. 1999a,b; Peterson et al. 1995; Brown and Braaten 1998; Changnon 1998; Frei et al. 1999; Easterling et al. 2000; Groisman et al. 1994, 1999a,c; Cayan et al. 2001). Precipitation has increased, the probability of a day with heavy precipitation has increased, spring snow cover has retreated, and pan evaporation has decreased.¹ Section 2 describes terminology and definitions of heavy and very heavy precipitation and high streamflow used throughout this paper. Sections 3 and 4 of this paper outline the changes in precipitation and snow cover over the United States. Could these changes be large enough to affect the surface component of the hydrological cycle, streamflow? Apparently so, as the first assessments of the streamflow changes over the United States (Lettenmaier et al. 1994; Lins and Michaels 1994) identified significant trends in the time series of natural (i.e., undisturbed by human activity) streamflow over the United States. Most of these trends were positive indicating an increase in mean annual streamflow, but analyses were not attempted to determine how the increase was distributed over various streamflow rates. Recently, however, Lins and Slack (1999) analyzed a network of streamflow stations and found that most of the statistically significant positive trends at individual stations are likely caused by increases in precipitation and reductions of snow cover extent.

¹This decrease in pan evaporation cannot be translated into a decrease of actual evaporation (Brutsaert and Parlange 1998; Golubev et al. 2000.)
Individual gauging stations have been confined to low and moderate streamflows. This finding is extremely important, because during periods of high streamflow, additional runoff increases the danger of river-related flooding, while during the period of low streamflow, additional water can be used for irrigation. The additional flow may also enhance river navigation and hydropower production. Lins and Slack (1999) did not relate changes in streamflow to precipitation, so it is important to understand how changes in precipitation relate to streamflow. Also, since Lins and Slack (1999) assess individual stations for statistically significant changes only, the question arises whether other types of analyses would show more statistically significant results if the noise in the time series was minimized.

If $S$ is the trend at a specific site, $i = 1, 2, \ldots, n$, where $n$ is the number of sites in a region, and $S$ describes a small portion of the total variance, $\sigma^2$, then a point by point search for statistically significant signals requires a very long record at each site. But, if the number of spatial degrees of freedom, $(\nu$, where $\nu < n)$ for a region like the United States is sufficiently high and $S$ is mostly of the same sign within a region, then we can expect that the area averaging will reduce the variance of the variable in question to $\sigma^2 / \nu$, while preserving the sign and magnitude of $S$, making the signal detectable. For annual temperatures over the conterminous United States, $\sigma$ is a one-digit value and the gain from area averaging for signal detection may be relatively small compared to daily heavy (high)–very heavy (very high) precipitation (streamflow), where $\nu$ is probably two orders of magnitude larger and the effect of area averaging on reducing $\sigma^2$ can be substantial. On the other hand, if $S$ varies strongly across the region, then area averaging can be counterproductive as $S$ approaches zero. Given differences in the hydrologic cycle across the United States, high streamflow changes over the contiguous United States are likely to be heterogeneous so a single countrywide assessment may be inadequate. For example, although heavy precipitation is responsible for flooding over most of the country and is likely to be the single source of high flow in the South and Southwest, snowmelt is the most probable cause of high flow in the mountains and the northern regions. There are also regions where both of these factors can operate and affect high streamflows.

The first concerns about the ongoing changes in the hydrological cycle were assessed by Budyko and Drozdov (1976), Wigley et al. (1980), Manabe et al. (1981), and recently by Houghton et al. (1996). Observational analyses have been made by Bradley et al. (1987), Groisman and Legates (1995), Iwashima and Yamamoto (1993), and Karl and Knight (1998). Model projections of a greenhouse-enriched atmosphere (Houghton et al. 1996) and the empirical evidence from the period of instrumental observations (Easterling et al. 2000) indicate an increasing probability of heavy precipitation events for many extratropical regions including the United States as global temperature increases. These projections and the observed increase of heavy precipitation raise the possibility of increased flooding, but snow cover changes induced by increasing temperature tend to smooth the seasonal cycle of streamflow, especially in high latitudes and elevations, thus reducing the intensity of spring snowmelt (Arnell et al. 1996; Georgievsky et al. 1996). Other important factors leading to high streamflow include hurricane landfalls along the Atlantic and Gulf coasts. Contemporary global climate models do not yet reliably reproduce hurricane activity and, thus, their behavior in climate change scenarios. Last, atmospheric circulation changes (e.g., related to the North Atlantic oscillation and/or Southern Oscillation) introduce specific large-scale patterns on each climatic signal over the United States, including that on streamflow.

The objective of this study is to determine when information about changes in mean and heavy precipitation, particularly during the months of high streamflow, can be expected to be reflected in changes of high streamflow. We note that mean runoff has been shown to be highly sensitive to changes in precipitation on an annual basis (Karl and Riebsame 1989), but it has never been analyzed for high streamflow rates. To this end, we selected the best possible network of collocated rain and streamflow gauges having more than 60 years of synchronous daily observations. With this network we assess the rela-
Fig. 1. (a) Examples of heavy and very heavy precipitation climatologies based on the number of days with precipitation above fixed thresholds. Values are mean annual number of days with 24-h daily precipitation above 50.8 mm (heavy) and 101.6 mm (very heavy).

(b) Examples of heavy and very heavy precipitation climatology based on frequency of precipitation events of various intensities. Values are maximum 24-h daily precipitation (mm) associated with 90th (heavy) and 99th (very heavy) percentiles of January and July precipitation in days with precipitation.

(c) Examples of heavy and very heavy precipitation climatologies based on average return period of the event. Values are maximum 24-h daily precipitation (mm) associated with 1- (heavy) and 20-yr (very heavy) return periods.
Fig. 2. Available stations with digitized daily precipitation data over the contiguous United States. (a) Stations with at least 25 yr of valid data points (9125 daily values or 83%) during the 1961–90 period, (b) stations with at least 83% of valid data points during the 1921–30 period, and (c) graph of the daily precipitation data availability by year since 1891.

Fig. 3. Linear trends (%/100 yr) of annual precipitation (1900–98) over the contiguous United States (updated from Karl and Knight 1998). Individual trends from 1221 Historical Climatology Network stations (Easterling et al. 1996) have been area averaged inside the U.S. climatic divisions (Guttman and Quayle 1996). Green dots indicate increasing and brown dots decreasing trends.

2. Heavy precipitation events: Definitions and climatology

Karl et al. (1996) and Groisman et al. (1999c) defined “heavy” daily precipitation as an event with precipitation above 50.8 mm (2 in.). More than 15% of daily summer precipitation totals in Louisiana make up these events, while during the cold season (Oct–Apr) in Bismarck, North Dakota, such an event has...
never occurred in the twentieth century. An alternative way to define heavy precipitation at a given site and season/month is to use the actual frequency distribution of precipitation. One can define the days with heavy precipitation as those days that have daily totals above specific percentiles of the distribution, for example, 90th, 95th, 99th, etc.; or those that occur once in X yr, for example, 1, 10, 20, or 50 yr, etc. Using this definition, heavy events can be simultaneously found at various thresholds depending on location and time of the year. Figure 1 shows examples of climatologies based on three alternative definitions of heavy and very heavy daily precipitation for the contiguous United States. The first definition is based on absolute threshold values (here we selected thresholds of 50.8 and 101.6 mm for heavy and very heavy daily precipitation, respectively). The second definition is based on the 90th and 99th percentiles of precipitation days throughout the year, and the third, on return periods of 1 and 20 yr. These climatologies were estimated from the daily precipitation data of 5873 stations over the contiguous United States for the past 50 yr with at least 25 yr of data during the period from 1961 to 1990 (Fig. 2).

The frequency and intensity of catastrophic events with loss of property, crops, or even human lives are the most important aspects of contemporary climate change, but events at the highest end of the precipitation/streamflow distribution can be short lived (hours to days) and quite localized. Therefore, precipitation/streamflow data from a spatially dense network with at least daily time resolution are required to understand the changes of these events. Homogeneous, long-term time series of these data are essential. Historically, climate change studies have been based on rather sparse networks. Up until recently, the only dataset of century-long daily U.S. precipitation time series from high quality data was from the U.S. Historical Climatology Network (Hughes et al.

Estimation of the percentiles within the precipitation distribution is based on days with precipitation excluding days without precipitation as calculated by Karl and Knight (1998) and recommended by Nicholls and Murray (1999).

![Annual number of days with P > 50.8 mm on the third day of the rain episode](image)

**Fig. 4.** National variations of the area-averaged annual frequency of the sequence (precipitation, precipitation, and heavy precipitation), where heavy precipitation is daily precipitation total above 50.8 mm (2 in.). A national trend of roughly 32%/100 yr is statistically significant at the 0.01 level.

![Regions used throughout this study and regionally averaged linear trends (1901–96) in the annual frequency of heavy precipitation events above 50.8 mm (2 in.) on the third consecutive day with measurable precipitation on each of the prior two days. Both the national trend and the trend in the South are statistically significant at the 0.01 level, the trend in the West is significant at the 0.05 level, and in the Midwest the trend is significant at the 0.10 level.](image)
Fig. 6. Annual number of days with very heavy precipitation (above 101.6 mm) over the (a.) Northwest and (b.) Upper Mississippi regions. Estimates are based on the network shown in Fig. 2. Results based on the subsets of stations that reported daily precipitation since the 1920s and (for the Upper Mississippi) since the 1900s are also shown. Stations with at least 50% of valid data in the 1920s (1900s) were included into these two subsets.

1992) which contained only 187 stations. This network appears to be sufficient for countrywide (large regions) generalizations used in analyses of heavy precipitation events (Karl and Knight 1998) or the days with precipitation above 50.8 mm (Groisman et al. 1999b,c), but to assess changes in daily precipitation above 100 mm, such a network is inadequate. Very rare events sometimes occur in the vicinity of a station and may go unreported. In order to address this problem and analyze the changes in the frequency of very heavy precipitation events, accumulated daily data were used from several thousand stations (Fig. 2). This enabled us to assess century-long trends in frequencies of very heavy daily precipitation events (those above 101.6 mm or 4 in.) over the contiguous United States as related to events above the 99th percentile for monthly and annual thresholds of streamflow events for river basins of various size.

Data holdings currently available at the U.S. National Climatic Data Center included Hughes et al. (1992), Kunkel et al. (1999a), Frei et al. (1999), and France (1998). Figure 2 shows that prior to 1948 (the year when routine digital archiving of meteorological information started in the United States) much less daily precipitation data are available for our analysis. Efforts to digitize more U.S. daily meteorological data for the pre-1948 period are currently under way at the National Climatic Data Center.

3. Precipitation changes

a. Seasonal and annual precipitation changes

Precipitation changes over the United States have not been linear over the twentieth century and there were decades (most noteworthy is the “dust bowl” of the 1930s), when significant large-scale anomalies occurred. However, when a linear approximation is used, precipitation totals during the twentieth century have increased significantly over most of the contiguous United States in all seasons except winter (Fig. 3, Table 1). The trends range from 7% to 15% per century during the summer and transition seasons (Table 1).

b. One-day heavy precipitation events

An early report about an increase of precipitation extremes in Japan and for a limited set of stations in the United States was provided by Iwashima and Yamamoto (1993). Based on daily data, trends in 1-day extreme precipitation events in the United States indicated more days with extreme daily precipitation totals. In particular, the number of days per year exceeding the 90th and 95th percentiles and 1-yr annual maximum daily precipitation amount have been increasing (Karl et al. 1996; Karl and Knight 1998). The increase in heavy and extreme events is amplified compared to the change in the mean, and this is consistent with worldwide analyses (Groisman et al. 1999b,c). Increases are largest for the southwest, midwest, and Great Lakes regions of the United States. The area of the United States experiencing excessive wetness appears to be increasing, particularly since the 1970s (Karl and Knight 1998; Kunkel et al. 1999a). This is consistent with long-term increases in precipitation totals over the contiguous United States.

c. Multiday heavy precipitation events

The frequencies of 2–7-day precipitation totals exceeding station-specific thresholds for one in 1-yr
TABLE 2. Climatology (1961–90) and linear trends for 1900–99 of the annual number of days with daily precipitation above 101.6 mm (very heavy precipitation events). The time series of the frequency of these events for six regions are shown in Figs. 6 and 7. Trend estimates are based on the long-term precipitation time series only (those available since the 1900s) and in four western regions are not representative for the region (and, thus, not shown). Double asterisks and “#” mark trends that are statistically significant at the 0.01 and 0.10 levels, respectively. Unknown implies inadequate data available at present.

<table>
<thead>
<tr>
<th>Region</th>
<th>Mean (days yr(^{-1}))</th>
<th>Return period (yr)</th>
<th>Linear trend, (% 100 yr)</th>
<th>Variance described by the trend (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest</td>
<td>0.072</td>
<td>14</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Missouri River Basin</td>
<td>0.024</td>
<td>41</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Upper Mississippi</td>
<td>0.067</td>
<td>15</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Northeast</td>
<td>0.079</td>
<td>13</td>
<td>69#</td>
<td>3</td>
</tr>
<tr>
<td>California and Nevada</td>
<td>0.209</td>
<td>5</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Southwest</td>
<td>0.009</td>
<td>114</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>South</td>
<td>0.336</td>
<td>3</td>
<td>36**</td>
<td>7</td>
</tr>
<tr>
<td>Midwest</td>
<td>0.121</td>
<td>8</td>
<td>33#</td>
<td>3</td>
</tr>
<tr>
<td>Southeast</td>
<td>0.327</td>
<td>3</td>
<td>15</td>
<td>1</td>
</tr>
</tbody>
</table>

and one in 5-yr recurrences are increasing (Kunkel et al. 1999a). Heavy precipitation can be of special concern when it falls on saturated soil. Groisman et al. (1999a) defined a heavy precipitation event as a daily precipitation total above 50.8 mm and then calculated the mean annual number of days with a 3-day sequence (precipitation, precipitation, heavy precipitation). As an extension of this analysis using updated data from (Hughes et al. 1992), we find a statistically significant (at the 0.01 level) national increase of 32%/100 yr in the sequences of such events (Figs. 4 and 5). The return period of these events varies from 15 yr in the Southwest and the Missouri River Basin, 1.3 yr in the South and Southeast, and 2–3 yr in the West and Midwest (Groisman et al. 1999a). Nationally, during the beginning of the century the sequences of these events at any location occurred on average roughly once every 4 yr, but now they occur approximately once every 3 yr.

d. One-day very heavy precipitation events

Figure 2 shows a significant difference between the first and the second halves of the century as related to data availability. This can bias trend analysis. This is clarified in Fig. 6. For the northwestern United States, Fig. 6a shows that in the first half of the century the precipitation network (as now digitized) is unable to capture many of the very heavy precipitation events compared with a denser network using all available data. Our averaging technique is based on a selection of a reference period with adequate data availability, 1961–90, and then area averaging of anomalies from the reference period. Based on this criteria, over ~30 long-term northwestern stations were available that operated continuously since the 1920s. Their data indicate that indeed it was rare to observe very heavy precipitation events at these stations, but clearly the difference between using all data and the data of stations available since the 1920s suggests that the network of 30 stations is inadequate. In the Upper Mississippi region (Fig. 6b), precipitation days defined with daily totals above 101.6 mm are also very rare (an average return period of 15 yr per event). However, Fig. 6 shows that the precipitation network digitized for this region (Kunkel et al. 1999a) is adequate to report century-long changes of these events. This is clearly seen by a comparison of the time series constructed using the data of all stations,
the data of stations operating since the 1920s, and the data of stations operating since the 1900s. Since 1910, the frequency of the very heavy precipitation events has gradually increased in the upper Midwest (throughout this paper we name this region Upper Mississippi although it includes Michigan state) by more than 50%/100 yr (statistically significant at the 0.01 level). Since 1897 in this region, there are approximately 100 stations that have continuously reported precipitation. Therefore, if we account for the high variability of very heavy precipitation events in two decades around 1900 and several years of high values around the turn of the century, the increase in the frequency of these events (since 1891 or since 1900) is statistically insignificant (Table 2).

We found that in all four westernmost regions of the contiguous United States the available data are inadequate to reproduce the changes of very heavy precipitation events (number of days with precipitation above 101.6 mm) on a century-long timescale, while in the eastern United States the amount of data cur-

Fig. 7. Same as Fig. 6 but for the Northeast, Midwest, South, and Southeast.

Fig. 8. Linear trends (1950–98) in (a) mean Mar snow cover and (b) the date of the last measurable snow on the ground. Dark areas indicate regions where these trends are statistically significant at the 0.05 level.
rently available is sufficient to do this. Figure 7 presents the changes in the area-averaged annual number of very heavy precipitation events for four regions in the eastern part of the United States. In each plot we show three time series constructed similarly to Fig. 6b. Table 2 provides a complete regional climatology of these events and the trend estimates constructed using the subset of these stations that were operational 50% of the time in the 1900s. It shows that in three of five regions of the eastern two-thirds of the contiguous United States, a significant increase in the frequency of very heavy precipitation events has occurred during the twentieth century. While the relative changes (above 30% per century in the Midwest and South or ~70%/100 yr in the Northeast) are large, the absolute values of these changes are small, for example, about 1 day in the South and only ~0.5 day in the Northeast per 1000 yr. On the other hand, the return periods of thus defined very heavy precipitation events have changed during the past century in the Midwest from 10 to 7 yr, in the South from 4 to 2.7 yr, and in the Northeast from 26 to 11 yr.

### Table 3. Reduction of variance of area-averaged characteristics of stream gauging stations over the contiguous United States during the month of maximum runoff compared to the mean variance of individual streamflow time series (ratio of variances). These characteristics were arithmetically averaged inside nine regions shown in Fig. 4 using 385 long-term gauging stations used by Lins and Slack (1999). The following characteristics have been considered: monthly normalized streamflow (STR), number of days with streamflow above the 90th and 99th percentiles and below the 10th and 1st percentiles (ND90, ND99, ND10, and ND01, respectively).

<table>
<thead>
<tr>
<th>Region</th>
<th>STR</th>
<th>ND90</th>
<th>ND99</th>
<th>ND10</th>
<th>ND01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest</td>
<td>2.5</td>
<td>3.1</td>
<td>7.5</td>
<td>3.3</td>
<td>3.8</td>
</tr>
<tr>
<td>Missouri River Basin</td>
<td>4.2</td>
<td>4.3</td>
<td>4.6</td>
<td>4.4</td>
<td>4.9</td>
</tr>
<tr>
<td>Upper Mississippi</td>
<td>2.7</td>
<td>3.5</td>
<td>5.8</td>
<td>2.8</td>
<td>6.6</td>
</tr>
<tr>
<td>Northeast</td>
<td>3.3</td>
<td>3.5</td>
<td>8.1</td>
<td>3.7</td>
<td>5.2</td>
</tr>
<tr>
<td>California and Nevada</td>
<td>3.1</td>
<td>2.9</td>
<td>3.0</td>
<td>2.3</td>
<td>3.2</td>
</tr>
<tr>
<td>Southwest</td>
<td>2.8</td>
<td>4.0</td>
<td>7.2</td>
<td>3.2</td>
<td>3.5</td>
</tr>
<tr>
<td>South</td>
<td>6.4</td>
<td>5.8</td>
<td>8.0</td>
<td>5.2</td>
<td>11.1</td>
</tr>
<tr>
<td>Midwest</td>
<td>2.8</td>
<td>3.0</td>
<td>5.0</td>
<td>4.5</td>
<td>11.1</td>
</tr>
<tr>
<td>Southeast</td>
<td>2.3</td>
<td>2.7</td>
<td>6.0</td>
<td>1.8</td>
<td>4.6</td>
</tr>
</tbody>
</table>
4. Snow cover changes

Analyses of snow cover information from satellite and in situ sources indicate a significant retreat of spring snow cover over the Northern Hemisphere and the United States during the past several decades (Houghton et al. 1996; Frei et al. 1999). Groisman et al. (1999a) reprocessed the U.S. cooperative daily measurements of snow depth since 1949 (NCDC 1998). Their analysis of several thousand stations shows that since 1950 there were significant and systematic changes in snow cover over the United States. Figure 8 shows the following:

- Along the Pacific coast of the United States (from Alaska to California) an early springtime retreat of snow cover has occurred during the past 49 yr (by 2–3 weeks).
- A significant national feature of the trends in snow cover extent is related to a springtime retreat. In Fig. 8a this retreat is apparent for March snow cover. This retreat is statistically significant (at the 0.05 level) in four regions (three of them along the Pacific coast).

An earlier onset of autumn snow cover over northern prairies and Upper Mississippi River Basin (by 1–2 weeks) was also evident, but over the eastern part of the United States a tendency for a delay was found of 1 week in the first autumn snow cover.

The earlier retreat of spring snow cover was first documented in California by Dettinger and Cayan (1995) and later confirmed by Johnson et al. (1999). The shorter period of snow accumulation in the West reduces the probability of a heavy spring snowpack, a primary source for spring runoff. Moreover, an increase in actual evaporation (Golubev et al. 2000) can be expected. Both these factors, especially the former, can contribute to streamflow decreases during the spring, a time of maximum streamflow.

5. Century-long mean monthly streamflow changes during the month of maximum streamflow

The Hydro-Climatic Data Network (Slack and Landwehr 1992) includes data from more than 1500 stream gauges but only 395 of them furnish a continuous daily record over the past 50 yr (Lins and Slack 1999). Only 34 sites, most of which are located in the northeastern quadrant of the contiguous United States, have century-long data. This severely limits analyses related to century-long trends in the streamflow (Lins and Slack 1999). Can we infer anything about the century-long changes in the streamflow, especially during the month of maximum streamflow, from their data as related to the longer and more spatially comprehensive precipitation data? This is practically important as related to whether the observed increase in precipitation has any bearing on streamflow extremes.

To address this issue, we focused on months of maximum mean streamflow and the preceding month.
Early spring (Mar–Apr) is the season with maximum streamflow in the eastern half of the country (Fig. 9). In the Upper Mississippi River Basin, Midwest, and Northwest these two months coincide with the snowmelt period. Over the Great Plains a broad (and not well defined) maximum streamflow is apparent in the warm season (Jun–Sep). Over the mountainous western half of the country the months of maximum streamflow coincide or directly follow the time of maximum snowmelt (from Mar in the South through Jun in the North). Along the western coast maximum streamflow occurs during the winter rainy season (Jan–Feb).

We calculated the mean and standard deviations of monthly mean streamflow for the period 1961–90 and standardized mean daily streamflow values (means were subtracted and the differences were divided by standard deviations). Standardization allows us to treat the streamflow time series equally for streams with relatively high and low flows. Otherwise, a large stream with a higher absolute variability will dominate in the area-averaged values.

The standardized time series were area averaged within nine large regions of the contiguous United States (shown in Figs. 5 and 8). Spatial averaging across nine large regions reduces the variance of the streamflow data, thereby eliminating unwanted spatial noise (Table 3). Table 3 shows the effect of arithmetical averaging of the data of 385 long-term gauging stations used by Lins and Slack (1999) inside these nine regions for the month of maximum streamflow. The noise reduction (sometimes by an order of magnitude) increases our ability to detect climatic signals (S), if they are present. Of course, only large-scale regionwide signals are identifiable through the area-averaging process. The entire concept of this study is based on the search of the large-scale changes (if they exist), thus justifying the use of regional and national spatial averaging.

Figure 10 shows the results of a “frozen network” experiment when the area-averaged monthly mean streamflow time series are compared with the same time series estimated strictly from the data of sites having at least 80 yr of observations. The analysis of the frozen network shows that only in the Northeast, Midwest, and the Upper Mississippi regions are we able to construct representative century-long streamflow time series. The streamflow time series in Fig. 10 demonstrate high interannual and interdecadal variability without a significant century-long systematic component. Only in the Upper Mississippi region is there a slight positive trend (1901–93) statistically significant at the 0.1 level. The trend describes only 3% of the time series variance. Streamflow in the...
month of maximum streamflow (early spring months in the above-mentioned three regions) is usually in the upper 90th percentile of the annual discharge distribution. Figure 10 shows that the monthly totals did not change (or slightly increased) during the past century over the three regions where a direct assessment is possible. This is, however, less than a quarter of the entire country. The number of streamflow gauges available for our analyses during the first 25 yr of the century is too small for inferring regional streamflow variations over other U.S. regions.

Figure 11 depicts the streamflow time series for six northern and western regions of the country where snowmelt constitutes a significant part to the runoff. In the two northwestern regions (Northwest and Missouri River Basin), where during the past 50 yr a significant retreat of snow cover has occurred (Fig. 8), a steady runoff increase during the month of maximum streamflow is evident from 1930 to 1970, but sharply reverses thereafter. This decrease, however, is not supported by similar changes in monthly streamflow in the preceding month as occurred before the 1970s or in other regions of the country. A gradual shift of the runoff of snowmelt to earlier dates may explain this phenomenon. Indeed, Fig. 12 shows a statistically sign-

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Fig. 12. Streamflow during the month of maximum streamflow and spring snow cover indicators over two northwestern regions of the contiguous United States.

Fig. 13. Streamflow variations during the month of maximum streamflow (solid line) over the southern and southeastern regions of the United States and total number of streamflow gauges available at each year (dashed line).
significant (at the 0.05 level) correlation between snow cover and maximum monthly streamflow for these two regions. Dettinger and Cayan (1995) documented the effect of earlier snowpack melting on streamflow in California, but the long-term streamflow gauges used here do not show such a relation. This is most likely because most of them are located at low elevations, where the month of maximum streamflow is related to winter storms rather than snowmelt.

In South and Southeast regions, the data available allows analysis of the streamflow trends during the month of maximum streamflow since the mid-1920s (Fig. 13). For both of these regions positive linear trends for the 1925–93 period are statistically significant at the 0.05 level and describe 9% and 6% of the time series variance, respectively. Removal of the last high flow year (1993) from the trend estimates makes the trend in the Southeast region insignificant.

The high-flow regime throughout the United States is highly heterogeneous and its interdecadal variations are also heterogeneous. We observed a decade of dry conditions over the Southwest in the late 1980s and no century-long changes in the Northeast or Midwest. During the past 70 yr we found a steady runoff in-

Fig. 14. Tendency of changes (dashed line) in the seasonal streamflow distribution in the northwestern United States and Missouri River Basin during the past decades.

Fig. 15. Streamflow (black, red, and blue dots) and nearby precipitation gauges (green dots) used in this analysis. The size and color of the dots in the streamflow maps depict gauges that report discharge from small river basins with areas less than 260 km$^2$ (100 mi$^2$, blue dots), with areas between 260 and 2590 km$^2$ (100 and 1000 mi$^2$, red dots), and with areas between 2590 and 25 900 km$^2$ (1000 and 10 000 mi$^2$, black dots). (top) The station selection based on at least 60 yr of streamflow data at each station from (Slack and Landwehr 1992) and a nearby (within 1° × 1° grid cell) station from the daily precipitation archive of Hughes et al. (1992). (bottom) The station selection based on the streamflow stations used by Lins and Slack (1999) that have long-term precipitation measurements inside the river basins.
TABLE 4. Maximum number of 1° × 1° grid cells per region with at least one streamflow gauged river basin and one precipitation gauge within this basin. The number of these cells quickly decreases prior to the mid-1930s due to the absence of sufficiently long-term homogeneous streamflow data.

<table>
<thead>
<tr>
<th>Region</th>
<th>Max no. of 1° × 1° grid cells in the region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest</td>
<td>17</td>
</tr>
<tr>
<td>Missouri River Basin</td>
<td>14</td>
</tr>
<tr>
<td>Upper Mississippi</td>
<td>25</td>
</tr>
<tr>
<td>Northeast</td>
<td>33</td>
</tr>
<tr>
<td>California and Nevada</td>
<td>11</td>
</tr>
<tr>
<td>Southwest</td>
<td>14</td>
</tr>
<tr>
<td>South</td>
<td>23</td>
</tr>
<tr>
<td>Midwest</td>
<td>41</td>
</tr>
<tr>
<td>Southeast</td>
<td>30</td>
</tr>
<tr>
<td>Lower Mississippi</td>
<td>11</td>
</tr>
</tbody>
</table>

crease (but with considerable high-frequency variability) in the South, Southeast, and in the Upper Mississippi River Basin. In the Northwest and Missouri River Basin an increase in streamflow was reversed during the past 25 yr during the period of an earlier onset of spring snowmelt. Schematically, this type of change is depicted in Fig. 14. A gradual decrease in the month of maximum streamflow (late spring in these two regions) is not supported by a decrease in the previous month and thus shifts the hydrograph (seasonal streamflow distribution) to earlier maximums. North of these two regions in western Canada, an earlier onset of the dates of maximum streamflow was also reported by Burn (1994).

6. National and regional relationships of high streamflow and heavy precipitation

a. Data

For several reasons, precipitation is not routinely monitored within the U.S. streamflow network. However, precipitation is the most intensely monitored element of the hydrological cycle in the United States. It is observed at more than 10 000 locations, and precipitation trends constitute the most reliable portion of information about the twentieth century changes in the hydrological cycle. First, we selected precipitation and streamflow stations that are both located within 1° × 1° grid boxes for correlative analysis using the century-long precipitation data (Hughes et al. 1992), and long-term (at least 60 yr of observations) streamflow data, unaffected by human activity (Slack and Landwehr 1992). For 337 streamflow stations with a shorter period of record (since 1948) we were able to select 1169 precipitation stations from the dataset shown in Fig. 2. These stations were located strictly inside the gauged streamflow river basins. This set of stations is shown in Fig. 15b and was used for correlative analyses of very heavy—very high events. We were able to identify 208 grid cells over the contiguous United States (Table 4). Examination of Fig. 15b (which contains the stations included in these cells) and Table 4 indicates that the area covered by 1° × 1° grid cells is quite small in the central and western United States, west of the Mississippi. In the eastern United States the number of sites with nearby streamflow and precipitation gauges is substantially higher. Therefore, our results east of the Mississippi River will be more reliable and conclusive.

b. National relationships

1) NATIONAL TRENDS

In general, systematic increases in precipitation should cause a general increase in streamflow over the contiguous United States, assuming no changes in evapotranspiration and watershed management. We know that there has been an increase of temperature across the United States amounting to nearly 0.5°C since the turn of the century (Karl et al. 1996). So, some increase in evapotranspiration is likely to ameliorate any increase in streamflow, but the effects are likely to be small (Karl and Riebsame 1989) compared to precipitation change. Karl and Riebsame (1989) provide relationships to estimate the impact of changes in precipitation and temperature on mean annual streamflow across the United States. Based on the observed change in national precipitation of 5% during the period of serially complete streamflow data

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8 Approximately 50 river basins in the Lins and Slack (1999) dataset do not have long-term precipitation gauges.
Fig. 16. (a) Contribution of various parts of daily precipitation/streamflow distribution to the linear trend of the total precipitation/streamflow over the contiguous United States during the 1939–99 period. Trends are presented in percent of the long-term mean values for the 1961–90 period. Ordinate is the trends in %/100 yr; abscissa is the semiclosed interval for five-percentile increments. Two variants of percentile calculations were used: in the first column, five-percentile increments were predefined using monthly daily data for the 1961–90 period and then averaged for the year/spring; in the second column, the percentiles were defined for the same period by selecting from annual/spring daily precipitation and streamflow events without partitioning by month. (b) The time series of the annual total contribution of the two upper class intervals of daily streamflow and precipitation events [their trends are shown in the upper-right panel of (a)].
Fig. 17. Variations of the annual number of days with high (very high) streamflow (red lines) and heavy (very heavy) precipitation (black lines) for gauges collocated in $1\degree \times 1\degree$ grid cells. Results of national averaging for the streamflow gauges that represent small river basins with areas less than $260$ km$^2$ (or $100$ mi$^2$), medium river basins with areas between $260$ and $2590$ km$^2$ ($100$ and $1000$ mi$^2$), and large river basins with areas between $2590$ and $25,900$ km$^2$ ($1000$ and $10,000$ mi$^2$) and collocated rain gauges shown in Fig. 15a. The 90th and 99th monthly percentiles of daily precipitation (during the days with precipitation) and streamflow were used to define heavy/high and very heavy/high events. Here, $N$ is the number of $1\degree \times 1\degree$ grid cells used in the national averaging; $R$ (correlation coefficient) between streamflow and precipitation is statistically significant at the $0.01$ level in all cases except for very heavy/high precipitation and streamflow in the small river basins.
Fig. 18. Same as Fig. 17 but for very heavy precipitation (black lines) and very high streamflow (red lines) events for the river basins that have precipitation gauges. Results of national averaging for the streamflow gauges and collocated rain gauges shown in Fig. 15b. Left column represents counts of the days with precipitation/streamflow above the 99th monthly percentiles (i.e., for each month at each site the 99th percentiles are used to define very heavy and very high events). Right column represents counts of the days with precipitation above the 99th annual percentiles and streamflow above the 99.7th annual percentiles for the eastern half of the conterminous United States (east of 95 W). In this case, the percentiles were selected to represent on average a threshold value exceeded about 1 day per year for both precipitation and streamflow. Note, however, the scales of the y axes in the right column have a twofold difference in variability.
Table 5. Probability of a day with precipitation annually and during the month of maximum streamflow. Estimates are based on the daily data from stations depicted in the top panel of Fig. 15 for the 1961–90 period. They can be used to scale the y axes in Figs. 19–23 to obtain the annual (monthly) values of days with precipitation above the 90th, 95th, and 99th percentiles of precipitation distribution.

<table>
<thead>
<tr>
<th>Region</th>
<th>Probability of a precipitation day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual</td>
</tr>
<tr>
<td>Northwest</td>
<td>0.29</td>
</tr>
<tr>
<td>Missouri River Basin</td>
<td>0.22</td>
</tr>
<tr>
<td>Upper Mississippi</td>
<td>0.25</td>
</tr>
<tr>
<td>Northeast</td>
<td>0.34</td>
</tr>
<tr>
<td>California and Nevada</td>
<td>0.15</td>
</tr>
<tr>
<td>Southwest</td>
<td>0.17</td>
</tr>
<tr>
<td>South</td>
<td>0.22</td>
</tr>
<tr>
<td>Midwest</td>
<td>0.29</td>
</tr>
<tr>
<td>Southeast</td>
<td>0.28</td>
</tr>
<tr>
<td>Lower Mississippi</td>
<td>0.26</td>
</tr>
</tbody>
</table>

(1939–93), their relationships yield a 16% increase in mean annual streamflow. The actual nationwide annual streamflow increase for this period was 20%. In order to present the most current values of the trend estimates, we recently obtained updates to the U.S. Geological Survey (USGS) national database with the most recent data ending during the 1999 hydrological year. We note that for the period 1939–99 the last year is a dry year (opposite to the extremely wet ending year of the 1939–93 period). The trend estimates changed to a 7% and 17% increase in precipitation and streamflow, respectively, for this period. But, the two- to threefold amplification of the streamflow increases compared to precipitation increases remains intact.

Of particular interest to us is whether such an amplification is apparent throughout all of the percentiles. Using the 1° × 1° grid cell paired streamflow and precipitation gauges we calculated the trends of annual and spring (generally the time of maximum streamflow) daily measurements of both precipitation and streamflow in five-percentile class intervals. This was derived by calculating quantiles related to the pentad percentiles based on the 1961–90 period. These quantiles were then used to define the class limits of the pentad percentiles and the trend in precipitation or streamflow was then calculated within each of these class intervals for each month of the year for the 1939–99 period. Subsequently, the observed trends were averaged across months and standardized to ensure that the trend estimates for different areas were equally weighted in our area-averaging procedure. For this purpose, we divided the annual/spring trends by the long-term mean annual/spring precipitation/streamflow, and multiplied by 100% to obtain the trend in percent per century. Results from each pair of the stations were arithmetically averaged within each of the grid cells, within each of the nine regions (Fig. 5), and finally area averaged across the contiguous United States.

Generally throughout this paper, we calculated precipitation/streamflow percentiles for each month separately. In the presence of a strong seasonal cycle in precipitation and streamflow, this approach may lead to very different values of these percentiles affecting the contribution of different months to the annual totals for each of the five-percentile intervals. To avoid this effect (and to test the robustness of the national conclusions), we applied an alternative method of evaluating the percentiles for both annual and seasonal daily precipitation. This was accomplished by calculating class limits of the percentiles without regard to month for the entire season or year during the 1961–90 period. Months of maximum precipitation or streamflow contribute enormously to the higher percentiles when this method is applied. However, Fig. 16 shows that both approaches give similar results regarding the contribution to the trends of the higher end of both precipitation and streamflow distributions.

Figure 16 indicates that the mean annual increase in streamflow (which can be determined by integrating across all five-percentile class intervals in Fig. 16...
There are different ideologies behind this and our approach. It is possible to define heavy/high values climatologically for each month or using the approach based on the annual quantiles. The latter approach is more practical from a flood-risk point of view in that it is not important to consider high flows of relatively low seasonal streamflow when they do not contribute to river flood stage.

### Table 6. Correlation between the annual number of days with daily precipitation and streamflow above selected monthly percentiles. Asterisks indicate correlations that are statistically significant at the 0.01 level.

<table>
<thead>
<tr>
<th>Region</th>
<th>90th percentile</th>
<th>99th percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest</td>
<td>0.7*</td>
<td>0.3</td>
</tr>
<tr>
<td>Missouri River Basin</td>
<td>0.3*</td>
<td>0.2</td>
</tr>
<tr>
<td>Upper Mississippi</td>
<td>0.7*</td>
<td>0.3</td>
</tr>
<tr>
<td>Northeast</td>
<td>0.6*</td>
<td>0.6*</td>
</tr>
<tr>
<td>California and Nevada</td>
<td>0.6*</td>
<td>0.2</td>
</tr>
<tr>
<td>Southwest</td>
<td>0.6*</td>
<td>0.3</td>
</tr>
<tr>
<td>South</td>
<td>0.6*</td>
<td>0.1</td>
</tr>
<tr>
<td>Midwest</td>
<td>0.6*</td>
<td>0.2</td>
</tr>
<tr>
<td>Southeast</td>
<td>0.6*</td>
<td>0.5*</td>
</tr>
<tr>
<td>Lower Mississippi</td>
<td>0.7*</td>
<td>0.5*</td>
</tr>
</tbody>
</table>

and using the scaling factor 0.61 to account for the period length) was actually 17% (a significant amplification compared to the 7% precipitation increase for the same period of 1939–99). While both the national trends in annual precipitation and streamflow for this period are barely statistically significant at the 0.05 level (linear trends describe only about 6% of the interannual time series variance), the national trends in their highest class (shown in Fig. 16B for the classes defined without regard to month) are more significant. During the 1939–99 period, linear trends describe 14% and 8% of this class interval’s variance for precipitation and streamflow, respectively. These changes are quite important, because nationwide, 20%–50% of annual streamflow (~80% in the extremely wet 1993 year) and 20%–30% of annual precipitation occurs during the small number of days with these heaviest or highest precipitation or streamflow events. Inspection of Fig. 16 indicates that changes in precipitation are amplified across most of the streamflow percentiles both during spring and annually. This is especially evident for the highest percentiles, for example, above the 95th percentile. This implies that streamflow generally amplifies changes of precipitation across the distribution over most of the contiguous United States, so heavy precipitation changes should directly affect changes for the high streamflow events. In the following section we examine this general characteristic in more detail and provide evidence to help explain exceptions we have noted. This is especially relevant to the seemingly conflicting results found by Lins and Slack (1999) with respect to changes in high streamflow.

2) **Annual relationships between the frequency of heavy/very heavy precipitation and high/very high streamflow**

Figure 17 shows the national average of the annual numbers of days with precipitation and streamflow above 90th and 99th monthly percentiles partitioned by the areas with long-term streamflow gauges. There were 248 river basins with areas of less than 25 900 km² (or 10 000 mi²). They were partitioned into three groups: small basins, the area less than 260 km² (100 mi²); medium basins, the area between 260 and 2590 km² (100 and 1,000 mi²); and large basins, the area above 2590 km² (1000 mi², but less than 25 900 km² or 10 000 mi²). In each month 90th and 99th percentiles were estimated separately for the 1961–90 period and the number of days above these station-specific thresholds were integrated for each year and then arithmetically averaged inside each group. Figure 1 provides information regarding the absolute values of these thresholds for January and July. Figure 17 complements the data displayed in Fig. 16 related to the significant relation between increases in precipitation and streamflow. Note a prominent correlation between annual frequencies of heavy precipitation and high streamflow at the collocated gauges. The relationship is weaker for the highest
Fig. 19. Mean number of days with precipitation and streamflow exceeding the 90th percentile of daily total precipitation and mean daily streamflow each month during the year. In order to convert the number of days with precipitation to mean annual numbers of days with precipitation (since precipitation does not occur every day), they should be scaled using the regional estimates of mean annual probability of days with precipitation (Table 5).

percentile and decreases for small river basins to a marginal 11% of common variance. This is not surpris-

ing, because for these small river basins with an area considered to be less than 260 km² the nearby pre-

1For the annual number of days with heavy precipitation, an additional “standardization” step was performed prior to area averaging. Percentiles of precipitation were estimated only for days with precipitation. Therefore, the number of days above these percentiles are very different for wet and dry areas within each group (or region). This spatial heterogeneity forces the stations in the wet subregions to dominate in the area-averaged counts of days with heavy precipitation. To properly weight these stations inside each group/region, each annual value at a station, i, was scaled by the factor \( f(i) = 365.25 / \text{NRD}(i) \), where \( \text{NRD}(i) \), \( i = 1, 2, \ldots, n \) is the long-term mean annual number of rainy days at station i, during the reference period of 1961–90. These rescaled values were area averaged (in this case arithmetically) and the regional mean value was then rescaled with the factor \( [\text{NRD(group/region)}]^{-1} \), where \( \text{NRD} = \Sigma f(i) / n \).
cipitation station within a 1° × 1° grid cell can be well outside the basin. Very heavy rainfall (often from a strong local convective cloud system) having a typical radii of correlation of several kilometers may differentially affect the weather station or the creek basin. This is less probable when we increase the area of the basin in our correlative assessment and for “large” river basins where frequencies of very heavy precipitation and very high streamflow are well correlated ($R^2 = 0.40$). Furthermore, Fig. 15 contains a substantial portion of small river basins in mountainous regions in the West, where the highest streamflow can be of snowmelt origin.

The correlation between the very high streamflow and very heavy precipitation increases significantly, when precipitation stations are selected strictly inside the appropriate river basins. Using the dense cooperative network (Fig. 15b), we found a significant increase in common variance at the national scale for each type of river basin (Fig. 18). The results in Fig. 18 also show the similarity between high and very high streamflow and heavy and very heavy precipitation, for the eastern half of the United States. An examination of Fig. 15 clearly indicates the boundaries of this analysis: some eastern states, for example, Minnesota, Florida, North Carolina, and Massachusetts, are underrepresented due to the absence of long-term time series with daily streamflow measurements. In order to test the robustness of the relationship in Figs. 16–18 (left-hand column), thresholds and methods of accounting were varied for very heavy precipitation and very high streamflow. We selected the annual 99th percentiles of precipitation and streamflow at each station without partitioning them into the monthly percentiles of precipitation and streamflow at each location and month were based on a percentile (R² = 0.40). Furthermore, Fig. 15 contains a substantial portion of small river basins in mountainous regions in the West, where the highest streamflow can be of snowmelt origin.

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c. Regional relationships

1) Method

The quantity of century-long homogeneous daily precipitation time series used in this study (Fig. 15a) does not allow selection of the neighboring precipitation gauges within the same streamflow catchments. Therefore, instead of a point by point intercomparison,¹⁴ the intercomparison of regionally averaged precipitation and streamflow characteristics was implemented. Regionally, we focused on the relationship between frequencies of daily heavy precipitation and daily high streamflow. The terms heavy and high at each location and month were based on a percentile approach (e.g., Fig. 1b). We calculated the number of days with precipitation/streamflow above the 90th, 95th, and 99th daily percentiles¹⁵ for each month and then averaged the number of days above these percentiles annually. The 90th percentile in streamflow occurs on average about three times each month. The 99th percentile threshold in our data implies that the regionally averaged monthly number of days with streamflow above this threshold can be reached approximately once per 3–4 yr each month. For precipitation, the frequency of occurrence of heavy (above the 90th percentile) and very heavy (above the 99th percentile) is much less and depends upon the prob-

¹¹The use of annual percentiles biases the assessment of heavy precipitation toward the warm season months over most of the contiguous United States (cf. Fig. 1b). But, in these months the runoff coefficient (ratio of runoff to precipitation) is the smallest due to high evaporation. Thus, an extraordinary winter storm may deliver less rain (or snow water equivalent) but contributes more efficiently to runoff than an average summer rainfall. That is why the correlation between very heavy–very high streamflow and precipitation days in Fig. 18 is stronger when we use monthly (instead of annual) percentiles for our intercomparison. On the other hand, an extraordinary high streamflow anomaly during the month of low flow that is less than that ordinary streamflow in the high flow season, while being important for ecology of the basin, may be less likely to result in flooding conditions.

¹²This intercomparison can be actually counterproductive, because the 1° vicinity does not necessarily occur in the same river basin.

¹³All percentiles were calculated for the same reference period of 1961–90. The number of days with precipitation above the 90th, 95th, and 99th percentiles was scaled as it is described in footnote 11 but was not scaled back in order to preserve the same scale in the y axes for different regions in the following Figs. 19–23. In these figures the right y axes identify the annual (or monthly) number of days with streamflow above the selected thresholds, while the left axes identify the number of 365 (or 28/30/31) rainy days that are above the selected thresholds. To calculate the annual (monthly) numbers of days with heavy (very heavy) precipitation, the values presented in these figures should be multiplied by the probability of rainy days presented in Table 5.
ability of days with precipitation. For example, according to Table 5 the 90th percentile for precipitation is substantially less frequent than the 90th percentile for streamflow and occurs on average about once each month in the Northeast or approximately once every second month in the Southwest.

For each $1^\circ \times 1^\circ$ grid cell, these statistics were regionally averaged for each region shown in Fig. 5. An additional subregion of the Lower Mississippi, which encompasses three states, Mississippi, Louisiana, and Arkansas, was also considered. Averaging within each region was performed strictly for the same set of grid cells for which both streamflow and precipitation daily values were available. This procedure generated homogeneous comparable time series of high streamflow and heavy precipitation for the period when all grid cells initially selected in the region have both types of data (usually since the mid-1930s). For precipitation, we were able to expand these time series back to 1910 for the entire country. For streamflow this was not possible. Also, our streamflow data end in 1993 because the last 6 yr were not available at the time of
this study. Therefore, we use the period from the 1930s to 1993 for our assessment of the relationship between heavy precipitation and high streamflow. Then, for those regions where this relationship is established, we infer the impact of our trends in heavy precipitation on runoff for the entire twentieth century.

2) **ANNUAL NUMBER OF DAYS WITH HEAVY PRECIPITATION AND HIGH STREAMFLOW**

Table 6 and Fig. 19 show that the annual frequencies of exceedance of the 90th percentile of streamflow and precipitation (based on the annual average of the monthly values) are correlated everywhere across the country. When we raised the threshold percentiles for the western and central United States, the correlation decreased (Fig. 20) and vanished completely for the 99th percentile (Fig. 21).

The absence of correlation between the 99th percentiles for the western and central United States indicates that at these extreme levels the relation between precipitation and streamflow extremes cannot be assumed. Reasons for the absence of correlation are likely due to the fact that, in the warm season, extremely heavy precipitation in dry regions and seasons of the western and central United States can be local and not well associated with river flow.
Additionally, the small amount of streamflow data and small radii of correlation for convective heavy precipitation make one or both of our time series unrepresentative for area-averaged precipitation/streamflow frequency in some of the regions. Also, a significant portion of extreme streamflow in the western and central United States is related to snowmelt. Trends in snowmelt are not necessarily related to heavy/extreme precipitation changes. These explanations are not applicable to the northeast and southeast United States and Lower Mississippi Valley where there are more extensive data and snowmelt trends are small. As a result, over the eastern regions the correlation between annual frequency of very heavy precipitation and very high streamflow is significant. The same is true for the Lower Mississippi region. So, for the eastern third of the United States, we can demonstrate that the interannual/interdecadal variability of mean annual heavy events of streamflow and precipitation is reasonably well correlated. Without more data it is not possible to show this for the central United States.

3) Number of days with daily heavy precipitation and high streamflow during the month of maximum streamflow

It is unlikely that there would be a strong correlation between concomitant monthly anomalies of total precipitation and streamflow in regions where a significant proportion of runoff occurs from snowmelt during the month of maximum streamflow. Neither should we expect a high correlation between frequencies of daily heavy precipitation and high streamflow events. Table 7 supports this notion. Among six regions of the northern and western United States, in the three most northwestern regions, the Northwest, the Missouri River Basin, and the Upper Mississippi, even the correlation between the number of days with precipitation and streamflow above the 90th percentile during the month of maximum streamflow is not significant. In the three other regions, the Northeast, West, and Southwest, 12%–19% of joint variance is explained during the month of maximum streamflow (Table 7).

Only in one of these six regions, the Northeast, is the correlation for the 99th percentile threshold statistically significant at the 0.01 level. Three features distinguished this region from the others. First, the period of maximum streamflow (Mar–Apr) is uniform for the entire region (except the northernmost part of Maine where maximum streamflow is observed in May). Second, the date of snow cover disappearance was not appreciably changed. Most importantly, frozen precipitation does not remain on the ground continuously through the cold season, and snow is not a large part of the cold season precipitation over the southern half of this region where most of our streamflow gauge sites are located. Therefore, we can expect that in this time of the year a larger portion (compared to other northern and western regions) of heavy and very heavy precipitation events are immediately available to contribute to the high flow events. Finally, the Northeast is well covered by our data (Fig. 15).

In two other regions, the Midwest and Southeast, a strong correlation at the 90th percentile and significant correlations at the 99th percentile during the month of maximum streamflow were found (Figs. 22
FIG. 22. Mean number of days with precipitation and streamflow exceeding the 90th percentile of daily total precipitation and mean daily streamflow during the month of maximum streamflow. The number of precipitation days is scaled (accounting for the fact that precipitation does not occur each day, but streamflow does). In order to convert the scaled number of days with precipitation to mean monthly values, they should be multiplied by the regional estimates of the mean probability of a day with precipitation during the month of maximum streamflow (Table 5).

Northeast, Midwest, and Southeast regions cover the eastern third of the United States including the Ohio and Tennessee River valleys. In these regions the available data allow us to conclude that there is a causal relationship between heavy and very heavy precipitation and high and very high streamflow during the period of the highest streamflow.

For the southern United States we did not find significant correlations partially due to insufficient data (e.g., no streamflow gauges were available for Oklahoma). When we separated the Lower Mississippi River valley region into a separate subregion and repeated our analysis, the results (not shown) indicate that the correlations during the month of maximum streamflow are similar to those for the Southeast.
7. Discussion and conclusions

When Lins and Slack (1999) reported century-long national trends in streamflow, they based their conclusions on the dataset that is heavily spatially biased to eastern and western regions of the contiguous United States. They found no national increase in very high streamflow based on a search of statistically significant changes at individual gauging stations. This conclusion has important implications and requires further refinement. We have shown that when the streamflow data are standardized across all months of the year they relate quite well to changes in precipitation across the entire distribution, including heavy precipitation and high streamflow. We also found this for the annual heavy precipitation and high streamflow values, that is, without regard to month over most of the country although the occurrence of these heavy/high events can be in different months. In fact, changes in precipitation are amplified by a factor of 2–3 across the full distribution. On the other hand, it would be inappropriate to generalize this result during months of maximum streamflow, where snowmelt is an important contributor to peak flow.

Whatever standardization technique and definition of heavy/high precipitation/streamflow were used, we found that during the past 50 yr over the regions of the contiguous United States, which were representatively covered by long-term streamflow observations (mainly east of Mississippi), the variations of high and very high streamflow and heavy and very heavy precipitation are similar. Table 7 shows that over the entire eastern United States our data are sufficient to support the existence of a fairly close relationship during the month of maximum streamflow between heavy precipitation and high streamflow events. Therefore, it is likely that trends in heavy precipitation over the Northeast and Southeast regions (Table 8) have led to increases in the frequency of high streamflow events during the month of maximum streamflow during the past century. On the other hand, in the western third of the United States, primarily where snowmelt has been occurring earlier and is also a major contributor to maximum and high streamflow, the increases in heavy precipitation are not likely to be reflected in century-long positive trends of high streamflow, consistent with the results of Lins and Slack (1999) and global climate model simulations (Lettenmaier et al. 1999). In the central part of the United States, streamflow data are sparse and it is difficult to make any definitive statement about joint changes in heavy precipitation events and high streamflow.

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study (Lins and Slack 1999). Our special thanks to Mathew J. Menne for assistance with a access to the USGS river basin boundary database and to two anonymous reviewers for thoughtful comments and recommendations. The NOAA Office of Global Programs has provided the support for this study.

References


——, D. R. Easterling, R. G. Quayle, P. Ambenje, and R. W. Knight: 1999a: Trends in precipitation and snow cover in

<table>
<thead>
<tr>
<th>Region</th>
<th>90th percentile</th>
<th>99th percentile</th>
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<tr>
<td>Northwest</td>
<td>0.08</td>
<td>0.11</td>
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<td>Missouri River Basin</td>
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<td>0.18</td>
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<tr>
<td>Upper Mississippi</td>
<td>1.17*</td>
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<tr>
<td>Northeast</td>
<td>0.60</td>
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<td>California and Nevada</td>
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<td>Southwest</td>
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<td>Lower Mississippi</td>
<td>0.7</td>
<td>−0.02</td>
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</table>


Johnson, T., J. Dozier, and J. Michaelsen, 1999: Climate change and Sierra Nevada snowpack. *IAHS Publ.*, 256, 63–70.


