HEAVY PRECIPITATION AND HIGH STREAMFLOW IN THE CONTIGUOUS UNITED STATES: TRENDS IN THE 20TH CENTURY

by

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ABSTRACT

Changes in several components of the hydrological cycle over the contiguous United States have been documented during the 20th century:

- An increase of precipitation and 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 we found a significant relationship 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 20th 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 conterminous United States during the past fifty 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 U.S. Most of these trends were positive indicating an increase in mean annual streamflow, but analyses were not attempted to discuss 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 gaging 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 were minimized?

If S is the trend at a specific site, i, i=1,2,…n, where n is the number of sites in a region, and S describes a small portion of the total variance, σ^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, (ν, where $\nu < n$) for a region like the USA 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 σ^2/ν, while preserving the sign and magnitude of S, making the signal detectable. For annual temperatures over the conterminous U.S., ν is a 1-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 ν is probably two orders of magnitude larger and the effect of area-averaging on reducing σ^2 can be substantial. On the other hand, if S varies strongly across the region, then area-averaging can be counter-productive as S approaches zero. Given differences in the hydrologic cycle across the USA, high streamflow changes over the contiguous U.S. 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

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[1] This decrease in pan evaporation cannot be translated into a decrease of actual evaporation (Brutsaert and Parlange, 1998; Golubev et al. 2000).

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 IPCC (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 (IPCC 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 USA 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 tends 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[2]. Contemporary global climate models do not yet reliably reproduce hurricane activity and, thus, their behavior in climate change scenarios. Lastly, atmospheric circulation changes (e.g., related to North Atlantic Oscillation and/or Southern Oscillation) introduce specific large-scale patterns on each climatic signal over the U.S., 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[3]. 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 co-located rain and streamflow gauges having more than 60 years of synchronous daily observations. With this network we assess the relationship of regional and national changes (as opposed to individual sites) of the probability of heavy precipitation and high streamflow. The results are summarized within nine large regions over the contiguous U.S. Sections 5 and 6 describe the streamflow and precipitation data sets and our results.

2. HEAVY PRECIPITATION EVENTS: DEFINITIONS AND CLIMATOLOGY

Karl et al. (1996) and Groisman et al. (1999a,b,c) defined “heavy” daily precipitation as an event with precipitation above 50.8 mm (2 inches). More than 15% of daily summer precipitation totals in Louisiana make up these events, while during the cold season (October to April) in Bismarck, North Dakota, such an event has never occurred in the 20th century. An alternative way to define “heavy” precipitation at a given site and season/month is to use the actual frequency distribution of precipitation.[4] One can define the days with “heavy

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[2] Hurricanes strike the Atlantic Coast of the Southeastern United States in the autumn months (usually characterized by low streamflow) and some of the most devastating floods of the 20th century have been related to hurricane landfall.

[3] This study was also motivated by a recommendation of an anonymous reviewer to the note of Pielke and Downton (1999) to analyze the two data sets (streamflow and precipitation over the United States) in a similar manner to resolve the potential contradictions and dissimilarities. We specifically excluded the large river basins (with areas above 25,900 km^2 or 10,000 mi^2) from the consideration. The assessment of interaction of large-scale multi-day heavy precipitation and high streamflow events over such basins is beyond the scope of this paper.

[4] 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).

precipitation" as those days that have daily totals above specific percentiles of the distribution, e.g., 90th, 95th, 99th, etc.; or those that occur once in X years, e.g., 1, 10, 20, or 50 years, 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 years. These climatologies were estimated from the daily precipitation data of 5873 stations over the contiguous United States for the past 50 years with at least 25 years of data during the period from 1961-1990 (Figure 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)[5] 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 data set of century-long daily U.S. precipitation time series from high-quality data was from the U.S. Historical Climatology Network (Hughes et al. 1992, updated) 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. 1999a,b), 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 (Figure 2). This enabled us to assess century-long trends in frequencies of "very heavy" daily precipitation events (those above 101.6 mm or 4 inches) over the contiguous U.S. as related to events above the 99th percentile for monthly and annual thresholds of streamflow events for river basins of various sizes.

Data holdings currently available at the U.S. National Climatic data Center included Hughes et al. (1992), Kunkel et al. (1999b), Frei et al. (1999), and NCDC (1998b). Figure 2 shows that prior to1948 (the year when routine digital archiving of meteorological information started in the USA) 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 underway at the U.S. 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 20th 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 20th century have increased significantly over most of the contiguous United States in

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[5] For streamflow from large river basins this time-frame is sometimes a week or more.

all seasons except winter (Figure 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 one-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, 95th percentiles and 1-year 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., 1999a,b; Easterling et al. 2000). Increases are largest for the Southwest, Midwest, and Great Lakes regions of the U.S. The area of the U.S. experiencing excessive wetness appears to be increasing, particularly since the 1970s (Karl and Knight, 1998; Kunkel, et al., 1999b). This is consistent with long-term increases in precipitation totals over the contiguous U.S.

c. Multi-day heavy precipitation events

The frequencies of 2 to 7-day precipitation totals exceeding station-specific thresholds for 1 in 1 year and 1 in 5-year recurrences are increasing (Kunkel et al 1999b). Heavy precipitation can be of special concern when it falls on saturated soil. Groisman et al. (1999c) 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 three-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%/100years in the sequences of such events (Figures 4 and 5). The return period of these events varies from 15 years in Southwest and Missouri River Basin, 1.3 years in South and Southeast, and 2 to 3 years in the West and Midwest (Groisman et al. 1999c). Nationally, during the beginning of the century the sequences of these events at any location occurred on average roughly once every four years, but now they occur approximately once every three years.

d. One-day “very heavy” precipitation events

Figure 2 shows a significant difference between the first and the second half of the century as related to data availability. This can bias trend analysis. This is clarified in Figure 6. For the Northwestern U.S., Figure 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, 1961-1990, 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 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 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 years per event). However, Figure 6 shows that the precipitation network digitized for this region (Kunkel et al. 1999b) 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 1920s, and the data of stations operating since 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%/100yrs (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 U.S., 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 time scale, while in the eastern U.S. the amount of data currently 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 U.S. In each plot we show three time series constructed similar to Figure 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 U.S., a significant increase in the frequency of “very heavy” precipitation events has occurred during the 20th century. While the relative changes (above 30% per century in Midwest and South or ~70%/100 yrs in Northeast) are large, the absolute values of these changes are small, e.g., about 1 day in the South and only ~0.5 day in the Northeast per 1,000 years. On the other hand, the return period of thus defined “very heavy” precipitation events have changed during the past century in the Midwest from 10 to 7 years, in the South from 4 to 2.7 years, and in the Northeast from 26 to 11 years.

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 (IPCC 1996; Frei et al. 1999). Groisman et al. (1999c) re-processed the USA cooperative daily measurements of snow depth since 1949 (NCDC 1998a). Their analysis of several thousand stations shows that since 1950 there were significant and systematic changes in snow cover over the USA. Figure 8 shows:

- 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 years (by two to three weeks).
- A significant national feature of the trends in snow cover extent is related to a springtime retreat. In Figure 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 one to two weeks) was also evident, but over the Eastern part of the United States a tendency for a delay was found of one 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 (Cayan et al. 2001) 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 U.S. Hydro-Climatic Data Network (Slack and Landwehr, 1992, updated) includes data from more than 1500 streamgauges but only 395 of them furnish a continuous daily record over the past 50 years (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 (March – April) is the season with maximum streamflow in the Eastern half of the country (Figure 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 (June to September). Over the mountainous western half of the country the months of maximum streamflow coincide or directly follow the time of maximum snowmelt (From March in the south through June in the north). Along the western coast maximum streamflow occurs during the winter rainy season (January-February).

We calculated the mean and standard deviations of monthly mean streamflow for the period 1961-1990 and standardized mean daily streamflow values (means were subtracted and the differences were divided by standard deviations)[6]. The standardized time series were area-averaged within nine large regions of the contiguous U.S. (shown in Figures 5 and 8). Spatial averaging across nine large regions reduces the variance of the streamflow data, thereby eliminating unwanted spatial noise (Table 3). The table shows the effect of arithmetical averaging of the data of 385 long-term gaging 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 years of observations. The analysis of the frozen network shows that only in the Northeast, Midwest, and the Upper Mississippi region, are we able to construct representative century-long streamflow time series. The streamflow time series in Figure 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 (1901-1993) 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

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[6] 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.

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[7]. This is, however, less than a quarter of the entire country. The number of streamflow gauges available for our analyses during the first 25 years 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 fifty years a significant retreat of snow cover has occurred (Figure 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, Figure 12 shows a statistically 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 (Figure 13). For both of these regions positive linear trends for the 1925-1993 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 years we found a steady runoff increase (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 years during the period of an earlier onset of spring snowmelt. Schematically, this type of change is depicted in Figure 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

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[7] Karl and Knight (1998) found insignificant changes in winter precipitation over Upper Mississippi and Midwest and an increase over Northeast during the 1910-1996 period. During the past fifty years, we observed only insignificant changes in snow cover (Figure 8) over these three regions. This implies that early spring streamflow over these three regions, a large portion of which is derived from snowmelt and winter precipitation, is not likely to appreciably change.

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 20th century changes in the hydrological cycle. First, we selected precipitation and streamflow stations that are both located within 1° x 1° grid boxes for correlative analysis using the century-long precipitation data (Hughes et al. 1992 updated), and long-term (at least 60 years of observations) streamflow data, unaffected by human activity (Slack and Landwehr, 1992 updated). For 337 streamflow stations with a shorter period of record (since 1948) we were able to select 1169 precipitation stations from the data set shown in Figure 2. These stations were located strictly inside the gauged streamflow river basins[8]. This set of stations is shown in Figure 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 Figure 15b (that contains the stations included into these cells) and Table 4 indicates that the area covered by 1 x 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 USA, assuming no changes in evapotranspiration and watershed management. We know that there has been an increase of temperature across the USA amounting to nearly 0.5° C since the turn of the Century (Karl et al 1996, updated through 1998). 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 USA. Based on the observed change in national precipitation of 5% during the period of serially complete streamflow data (1939-1993), 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 USGS National data base[9] the most recent data ending during the 1999 hydrological year. We note that for the period 1939-1999 the last year is a dry year (opposite to the extremely wet ending year of the 1939-1993 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°x1° 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 5-percentiles 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

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[8] Approximately 50 river basins in the Lins and Slack (1999) data set do not have long-term precipitation gauges.

[9] http:\\waterdata.usgs.gov\nwis-w\US\.

month of the year for the 1939-1999 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 U.S.

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 5-percentiles. 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 1961-1990 period. Months of maximum precipitation or streamflow contribute enormously to the higher percentiles when this method is applied[10]. However, Figure 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 5-percentile class intervals in Figure 16 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 1939-1999). 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 Figure 16B for the classes defined without regard to month) are more significant. During the 1939-1999 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 to 50% of annual streamflow (~ 80% in the extremely wet 1993 year) and 20% to 30% of annual precipitation occurs during the small number of days with these heaviest or highest precipitation or streamflow events. Inspection of Figure 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 quantiles, e.g., above the 95th percentile. This implies that streamflow generally amplifies changes of precipitation across the distribution over most of the contiguous U.S., 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.

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[10] There are different ideologies behind this and our approaches. 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.

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 km^2 (or 10,000 mi^2) [11]. They were partitioned into three groups: small basins, the area less that 260 km^2 (100 mi^2), medium basins, the area between 260 and 2,590 km^2 (100 and 1,000 mi^2); and "large" basins, the area above 2,590 km^2 (1,000 mi^2, but less than 25,900 km^2 or 10,000 mi^2). In each month 90th - and 99th -percentiles were estimated separately for the 1961-1990 period and the number of days above these station-specific thresholds were integrated for each year and then arithmetically averaged inside each group[12]. 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 co-located gauges. The relationship is weaker for the highest percentile and decreases for small river basins to a marginal 11% of common variance. This is not surprising, because for these small river basins with an area considered is less than 260 km^2 and the nearby precipitation 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, Figure 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 (Figure 15b), we found a significant increase in common variance at the national scale for each type of river basin (Figure 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 U.S. An examination of Figure 15 clearly indicates the boundaries of this analysis: some eastern states, e.g., Minnesota, Florida, North Carolina, 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 Figures 16 through Figure 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

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[11] The data set selected by Lins and Slack (1999) contains 11 hydrological stations that measure discharge from river basins with area from 25,900 km^2 to 60,000 km^2 and two stations that measure the total runoff from huge areas of ~250,000 km^2. These 13 stations were specifically excluded from our comparison with single precipitation gauge data.

[12] For 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 sub-regions 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 station, i, was scaled by the factor $f(i)=365.25/NRD(i)$, where NRD(i), i=1,2,…n is the long term mean annual number of rainy days at station, i, during the reference period 1961-1990. These re-scaled values were area-averaged (in this case arithmetically) and the regional mean value was then re-scaled with the factor $[NRD(group/region)]^{-1}$, where $NRD = \Sigma f(i)/n$.

precipitation and streamflow at each station without partitioning them into the monthly percentiles[13], varied the upper thresholds, considered the eastern U.S. separately (one of these tests is shown in the right column of Figure 18), and averaged the maximum annual values of precipitation / streamflow over the large, medium, and small river basins. After these tests it became apparent that ***over the contiguous United States representatively covered with long-term streamflow observations, i.e., over the eastern half, high and very high streamflow and heavy and very heavy precipitation covary and the relative variations in streamflow tend to be higher than precipitation.***

c. Regional relationships

1) Method

The quantity of *century-long* homogeneous daily precipitation time series used in this study (Figure 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 term "heavy" and "high" at each location and month was 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 percentiles[15] 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 three to four years each month. For precipitation, the frequency of occurrence of "heavy" (above 90th percentile) and "very heavy" (above 99th percentile) is much less and depends upon the probability 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° x 1° grid cell, these statistics were regionally averaged for each region shown in Figure 5. An additional sub-region of Lower Mississippi that encompasses three states, Mississippi, Louisiana, and Arkansas was also considered. Averaging within each region was

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[13] The use of annual percentiles biases the assessment of heavy precipitation toward the warm season months over most of the contiguous U.S. (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 Figure 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.

[14] This intercomparison can be actually counter-productive, because the 1° vicinity does not necessarily occur in the same river basin.

[15] All percentiles were calculated for the same reference period of 1961-1990. The number of days with precipitation above 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 y-axes for different regions in the following figures 19 through 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.

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 six years 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 20th century.

2) Annual number of days with heavy precipitation and high streamflow

Table 6 and Figure 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 (Figure 20) and vanished completely for the 99th percentile (Figure 21).

The absence of correlation between 99th percentiles for the Western and Central United States indicates that at these extreme levels the relation between precipitation and streamflow extremes can not 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 West and Central USA 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 West and Central USA 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 U.S. 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 are reasonably well correlated. Without more data it is not possible to show this for the Central U.S.

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 U.S., 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 to 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 (March-April) 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 (Figure 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 (Figures 22 and 23). 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 sub-region and repeated our analysis, the results (not shown) indicate that the correlations during the month of maximum streamflow are similar to those for Southeast.

7. DISCUSSION AND CONCLUSIONS

When Lins and Slack (1999) reported century-long national trends in streamflow, they based their conclusions on the data set that is heavily spatially biased to eastern and western regions of the contiguous U.S. They found no national increase in very high streamflow based on a search of statistically significant changes at individual gaging 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, i.e., 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 two to three 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 fifty years over the regions of the contiguous United States, that 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 increase 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 USA, 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 USA, 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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LIST OF TABLE CAPTIONS.

Table 1. Linear trends in mean seasonal precipitation area-weighted over the contiguous United States for period 1910-96. Trends are statistically significant (at the 0.01 level) except during winter.

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 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 gaging stations used by Lins and Slack (1999). The following characteristics have been considered: monthly normalized streamflow (S), number of days with streamflow above the 90th and 99th percentiles and below 10th and 1st percentiles (ND90, ND99, ND10, and ND01, respectively).

Table 4. Maximum number of 1° x 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 mid-1930s due to the absence of sufficiently long-term homogeneous streamflow data.

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

Table 7. Correlation between the number of days with daily precipitation and streamflow above the 90th and 99th percentiles during the month with maximum runoff. Double asterisks reflect statistical significance at the 0.01 level.

Table 8. Linear trends (days/100yrs) of the number of days with daily precipitation above selected monthly percentiles during the month of maximum precipitation during 1902-1996. Asterisks and "#" mark trends that are statistically significant at the 0.05 and 0.10 levels, respectively. These estimates are based on the century-long time series of 110 precipitation stations co-located with streamflow gauges as in Fig. 15a.

Table 1. Linear trends in mean seasonal precipitation area-weighted over the contiguous United States for period 1910-96. Trends are statistically significant (at the 0.01 level) except during winter.

Season	Winter	Spring	Summer	Autumn
Linear trend (%/100 yr.)	0	10	7	15

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.

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

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 gaging stations used by Lins and Slack (1999). The following characteristics have been considered: monthly normalized streamflow (S), number of days with streamflow above the 90th and 99th percentiles and below 10th and 1st percentiles (ND90, ND99, ND10, and ND01, respectively).

Region	Ratio of the variances				
	STR	ND90	ND99	ND10	ND01
Northwest	2.5	3.1	7.5	3.3	3.8
Missouri River Basin	4.2	4.3	4.6	4.4	4.9
Upper Mississippi	2.7	3.5	5.8	2.8	6.6
Northeast	3.3	3.5	8.1	3.7	5.2
California & Nevada	3.1	2.9	3.0	2.3	3.2
Southwest	2.8	4.0	7.2	3.2	3.5
South	6.4	5.8	8.0	5.2	11.1
Midwest	2.8	3.0	5.0	4.5	11.1
Southeast	2.3	2.7	6.0	1.8	4.6

Table 4. Maximum number of 1° x 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 mid-1930s due to the absence of sufficiently long-term homogeneous streamflow data.

Region	Maximum number of 1° x 1° grid cells in the region
Northwest	17
Missouri River Basin	14
Upper Mississippi	25
Northeast	33
California & Nevada	11
Southwest	14
South	23
Midwest	41
Southeast	30
Lower Mississippi	11

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.

Region	Probability of a precipitation day	
	Annual	Month of maximum streamflow
Northwest	0.29	0.31
Missouri River Basin	0.22	0.24
Upper Mississippi	0.25	0.27
Northeast	0.34	0.36
California & Nevada	0.15	0.18
Southwest	0.17	0.15
South	0.22	0.24
Midwest	0.29	0.33
Southeast	0.28	0.30
Lower Mississippi	0.26	0.28

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

Region	90th -percentile	99th –percentile
Northwest	0.7**	0.3
Missouri River Basin	0.3**	0.2
Upper Mississippi	0.7**	0.3
Northeast	0.6**	0.6**
California & Nevada	0.6**	0.2
Southwest	0.6**	0.3
South	0.6**	0.1
Midwest	0.6**	0.2
Southeast	0.6**	0.5**
Lower Mississippi	0.7**	0.5**

Table 7. Correlation between the number of days with daily precipitation and streamflow above the 90th and 99th percentiles during the month with maximum runoff. Double asterisks reflect statistical significance at the 0.01 level.

Region	90th percentiles	99th percentiles
Northwest	0.13	0.10
Missouri River Basin	0.05	0.12
Upper Mississippi	0.09	0.14
Northeast	0.37**	0.58**
California & Nevada	0.35**	0.16
Southwest	0.44**	0.12
South	0.00	0.12
Midwest	0.56**	0.48**
Southeast	0.77**	0.48**
Lower Mississippi	0.68**	0.16 (0.64** for the 95th percentile)

Table 8. Linear trends (days/100yrs) of the number of days with daily precipitation above selected monthly percentiles during the month of maximum precipitation during 1902-1996. Asterisks and "#" mark trends that are statistically significant at the 0.05 and 0.10 levels, respectively. These estimates are based on the century-long time series of 110 precipitation stations co-located with streamflow gauges as in Fig. 15a.

Region	90-percentile	99-percentile
Northwest	0.08	0.11
Missouri River Basin	0.15	0.18
Upper Mississippi	1.17#	0.15
Northeast	0.60	0.33*
California & Nevada	-0.71	0.10
Southwest	0.80	0.23
South	1.19#	0.20
Midwest	-0.67	-0.21
Southeast	-0.10	0.31*
Lower Mississippi	0.7	-0.02

LIST OF FIGURE CAPTIONS.

Figure 1. **A**. Examples of “heavy” and “very heavy” precipitation climatology based on the number of days with precipitation above fixed thresholds. Values are mean annual number of days with 24-hour 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-hour daily precipitation (mm) associated with 90-(heavy) and 99 (very heavy) -percentiles of January and July precipitation in days with precipitation.
C. Examples of “heavy” and “very heavy” precipitation climatology based on average return period of the event. Values are maximum 24-hour daily precipitation (mm) associated with 1 (heavy) and 20 (very heavy) year return periods.

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Figure 5. 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 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.

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

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Figure 9. Months with maximum streamflow from streamflow gauges used in this analysis.

Figure 10. Mean monthly streamflow during the month of maximum streamflow (black solid line) over northern and northeastern regions of the United States and total number of streamflow gauges available at each year (red dashed line). A frozen network of streamflow gauges with at least 80 years of data shows the same variations, but with higher variability (green line). The number of gauges in the frozen network are 10, 5, and 4 for the Northeast, Midwest, and Upper Mississippi, respectively.

Figure 11. Mean monthly streamflow during the month of maximum streamflow (black solid line) and the preceding month (green line) over the northern and western regions of the United States. The total number of streamflow gauges available at each year is also shown (red dashed line).

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

Figure 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).

Figure 14. Tendency of changes (dashed line) in the seasonal streamflow distribution in the northwestern U.S. and Missouri River Basin during the past decades.

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Figure 17. Variations of the annual number of days with high (very high) streamflow (red lines) and heavy (very heavy) precipitation (black lines) for gauges co-located in 1° x 1° grid cells. Results of national averaging for the streamflow gauges that represent small river basins with area less than 260 km^2 (or 100 mi^2); medium river basins with areas between 260 km^2 and 2,590 km^2 (100 and 1,000 mi^2); and large river basins with areas between 2,590 km^2 and 25,900 km^2 (1,000 and 10,000 mi^2) and co-located 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° x 1° 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.

Figure 18. Same as Figure 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 co-located 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 presents counts of the days with precipitation above the 99th annual percentiles and streamflow above the 99.7th annual percentiles for eastern half of the conterminous U.S. (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 right column have a twofold difference in variability.

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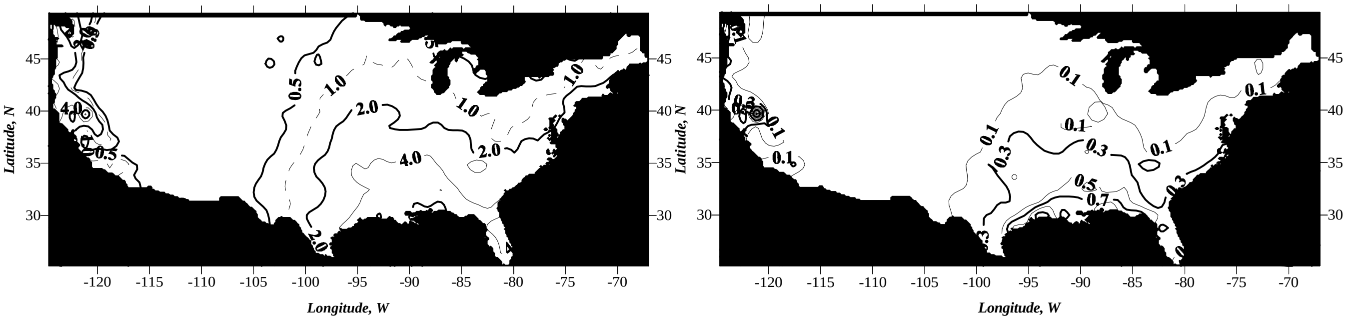
Figure 20. Same, as Fig. 19 but for the 95th percentile.

Figure 21. Same, as Fig. 19 but for the 99th percentile.

Figure 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).

Figure 23. Same as Fig. 22 but for the 99th percentile and the Eastern United States.



HEAVY

VERY HEAVY

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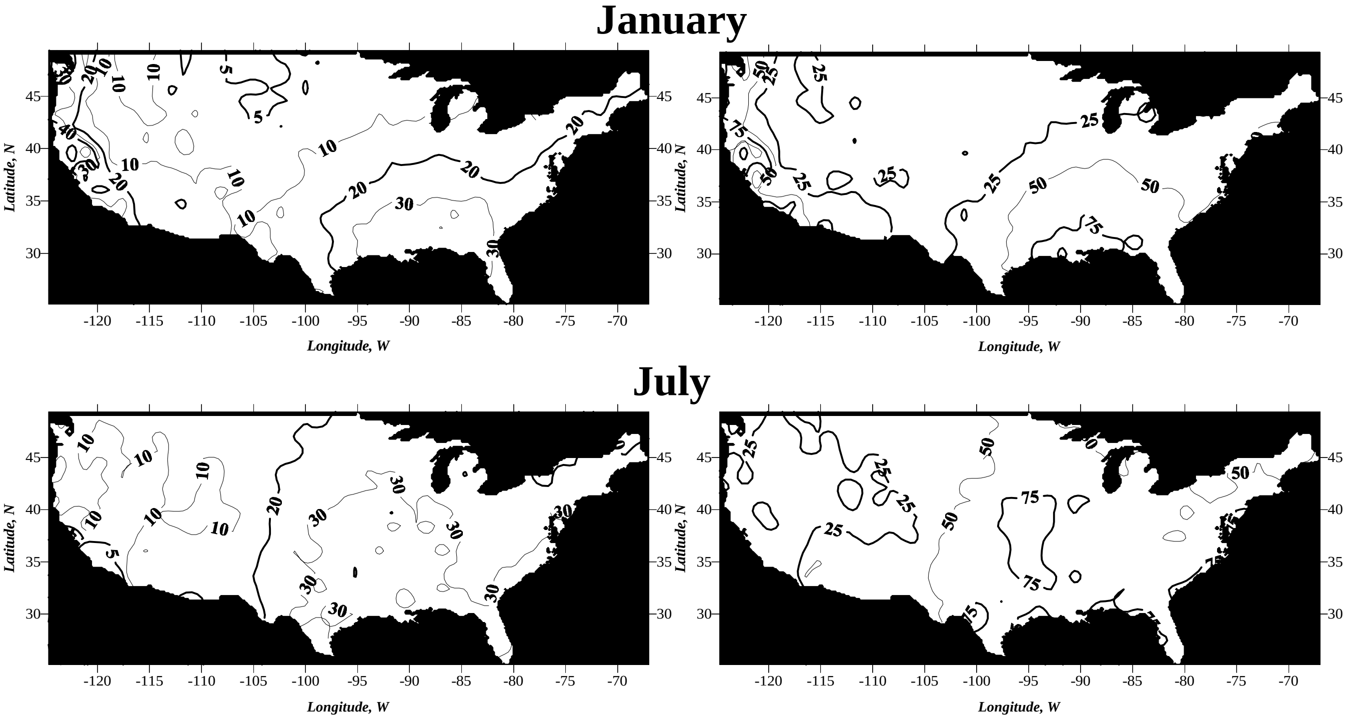
January

July

HEAVY

VERY HEAVY

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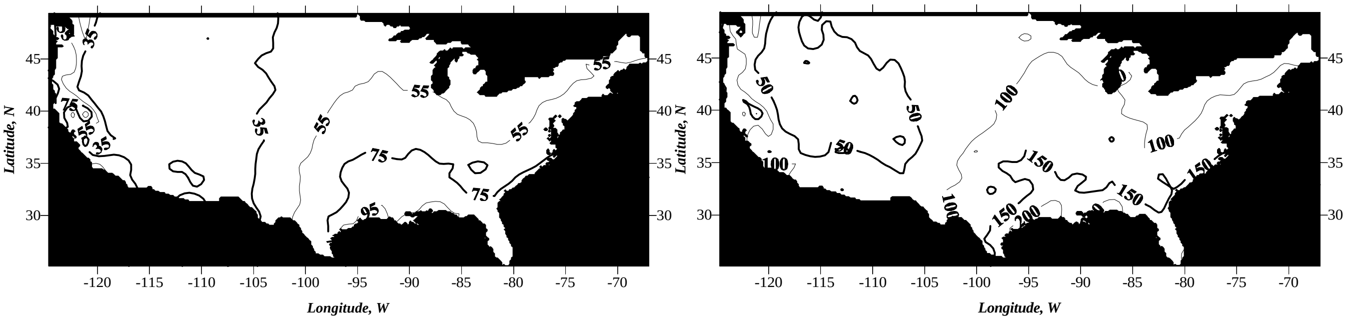

HEAVY

VERY HEAVY

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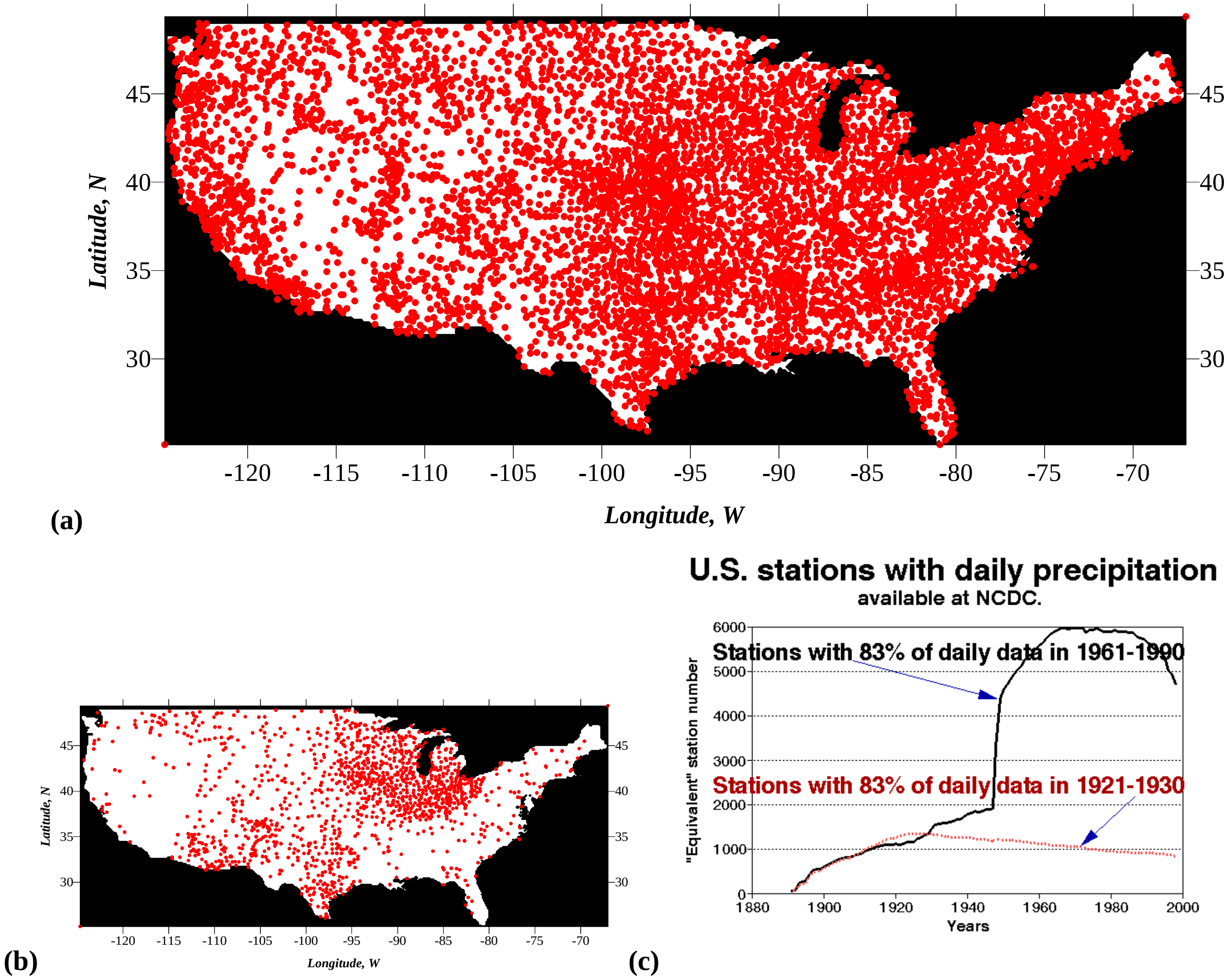

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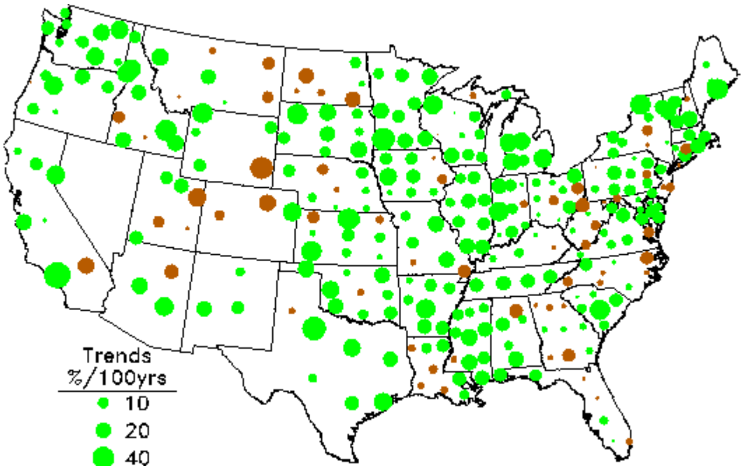

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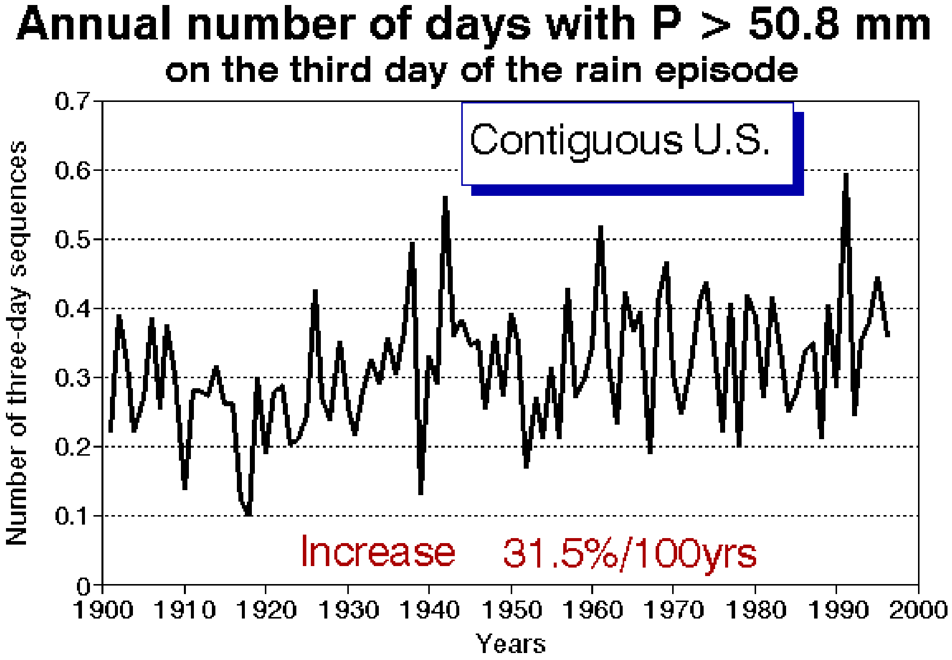

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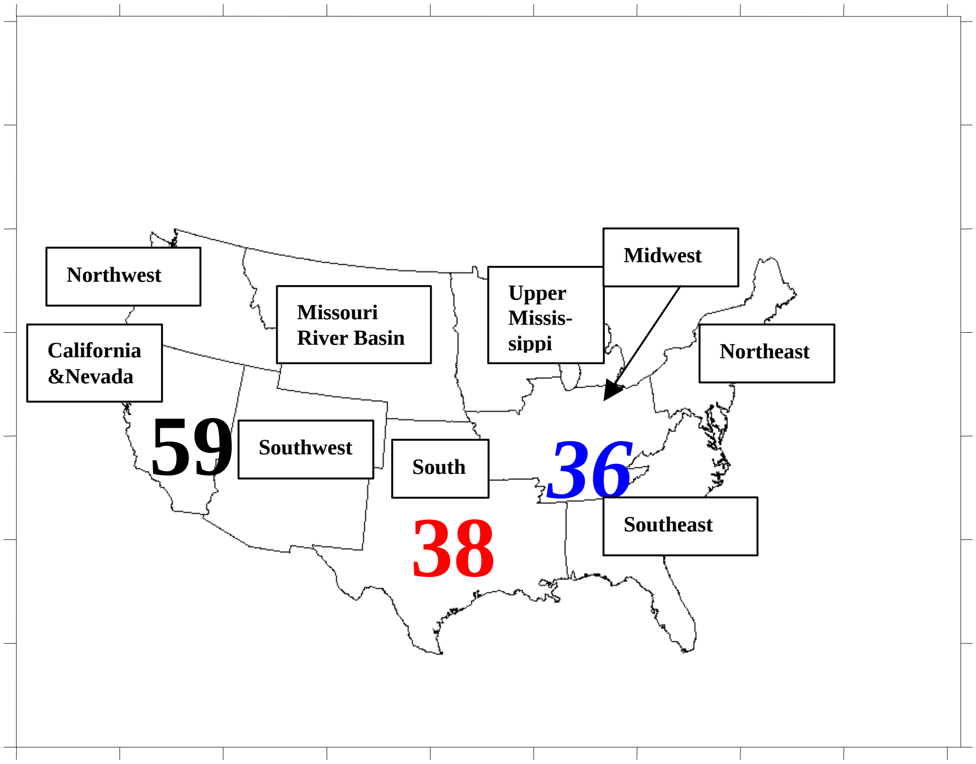

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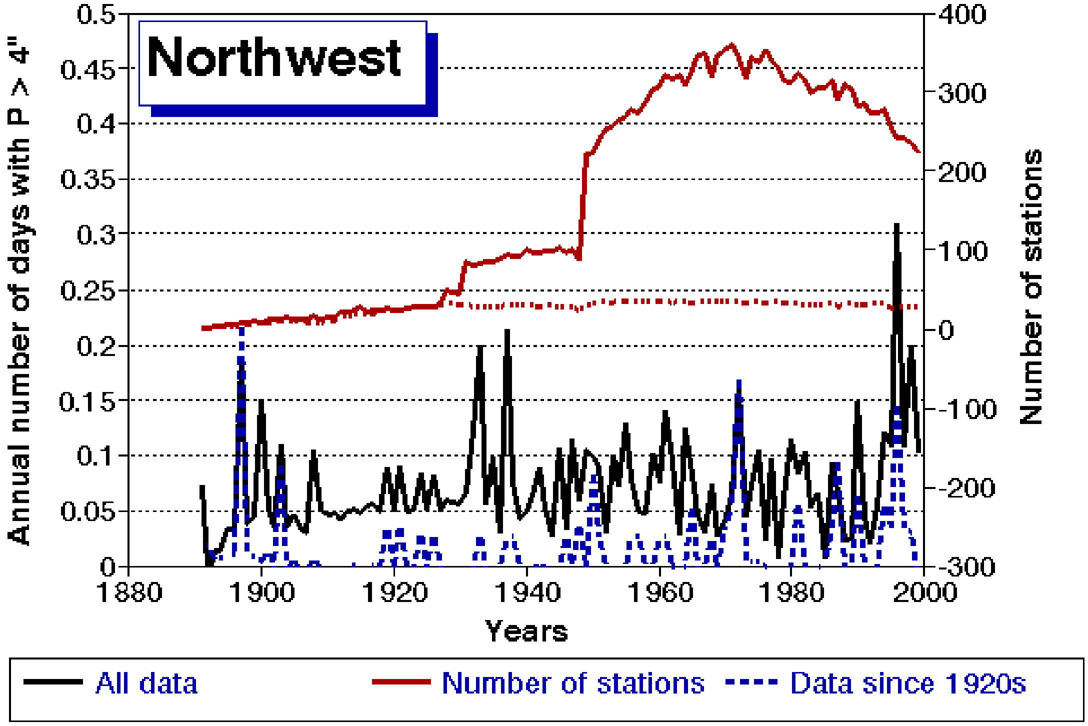
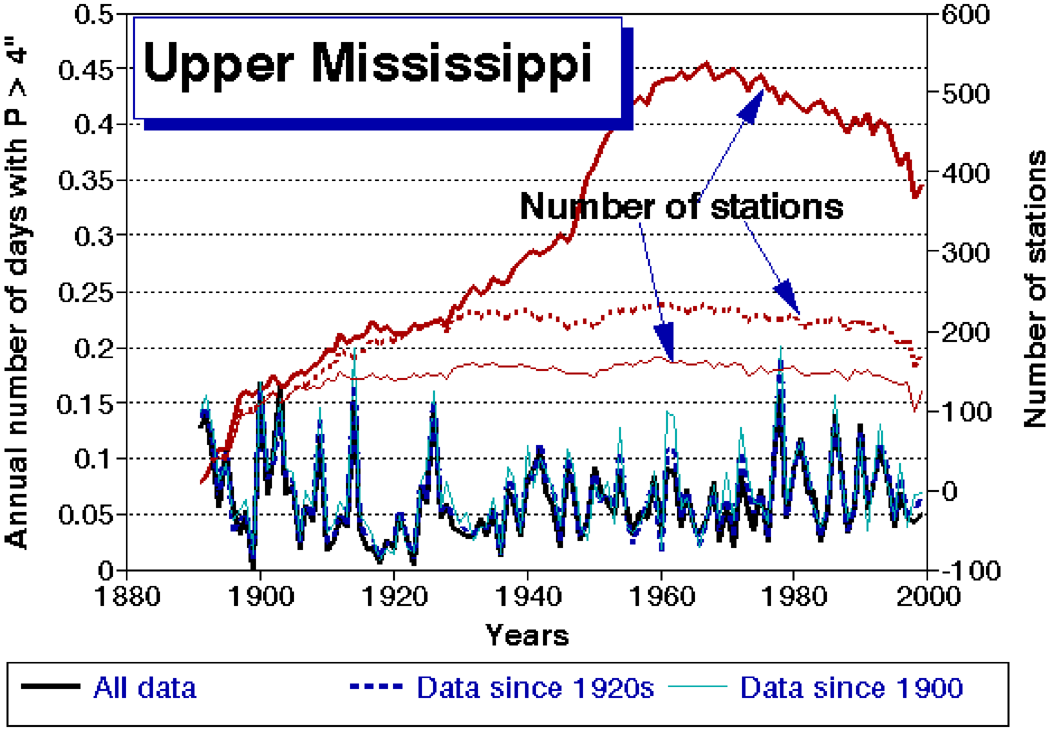


A.



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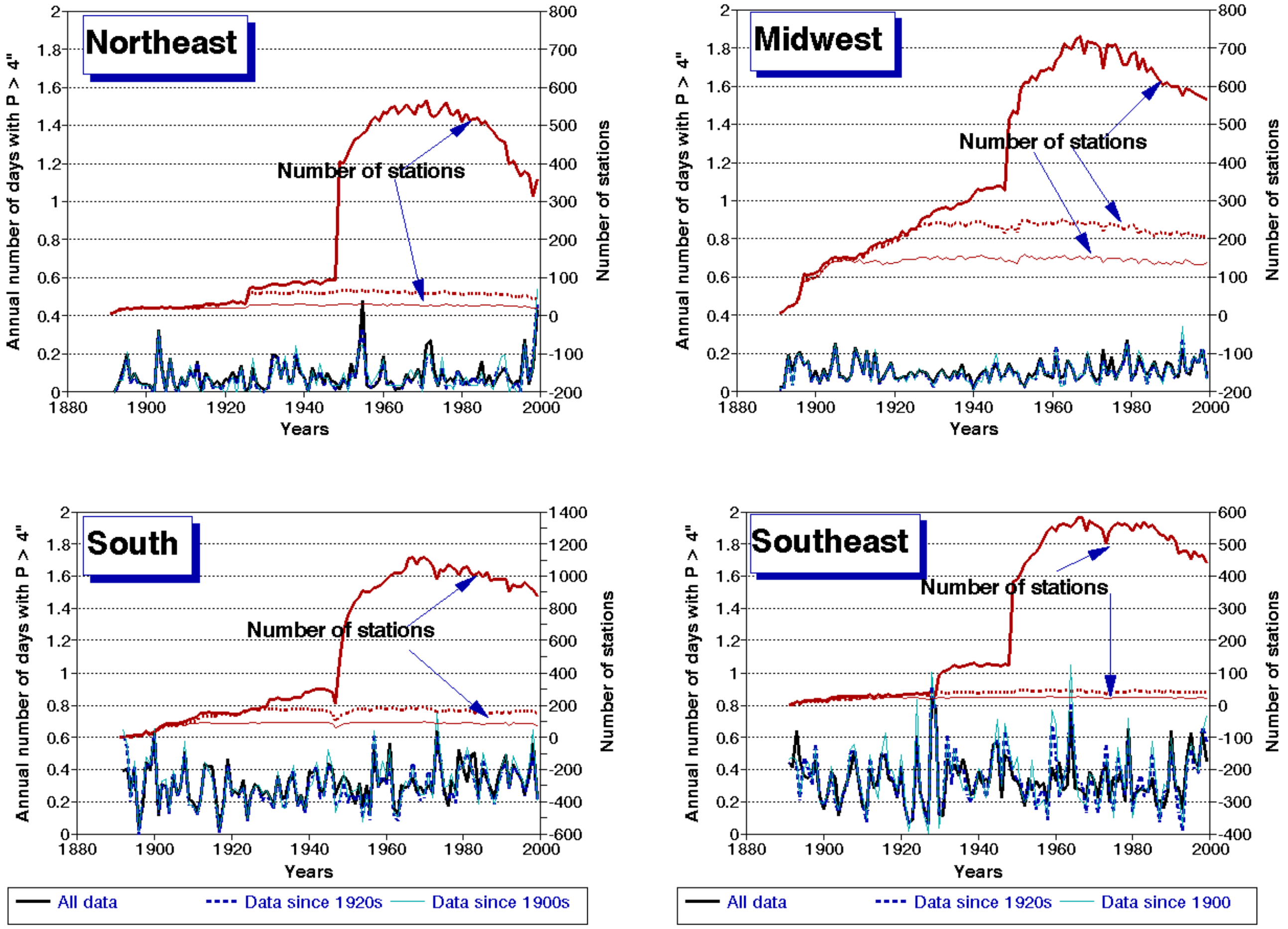

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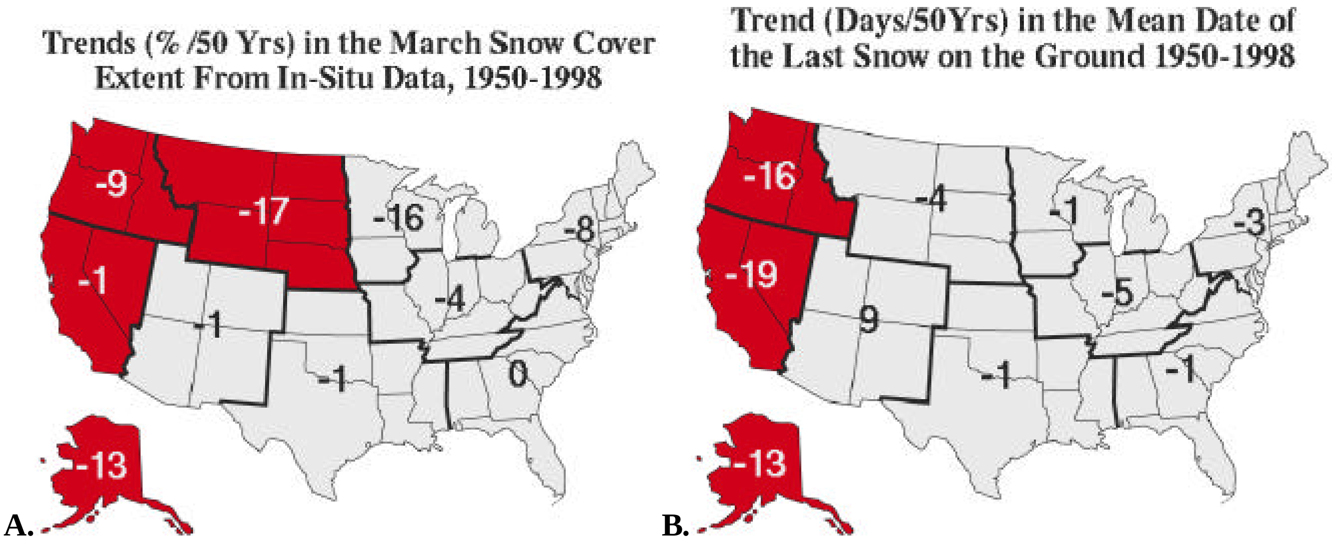

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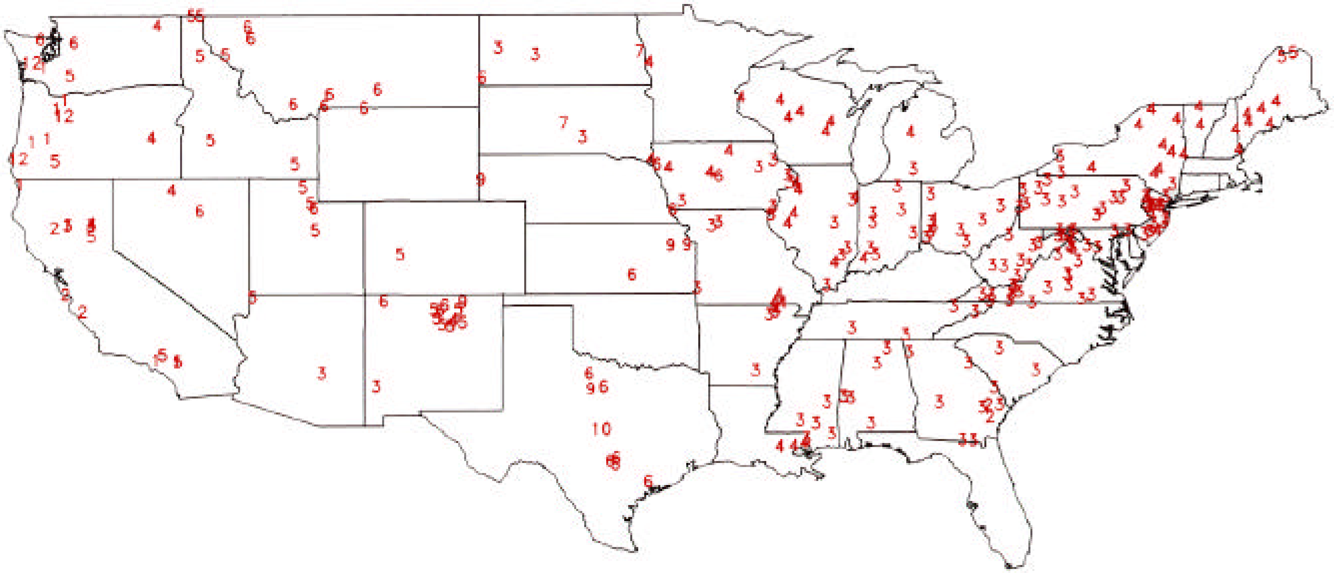

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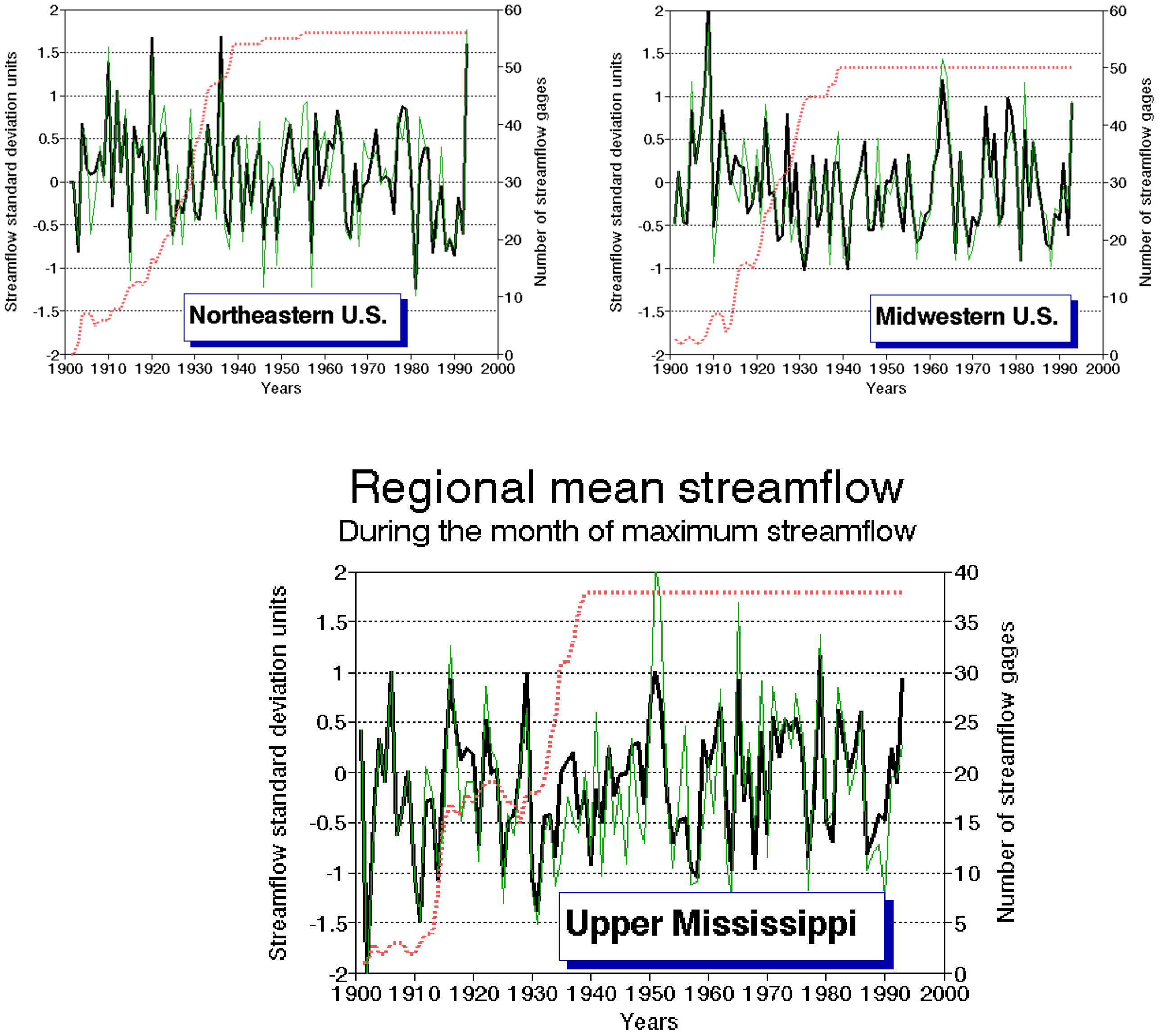

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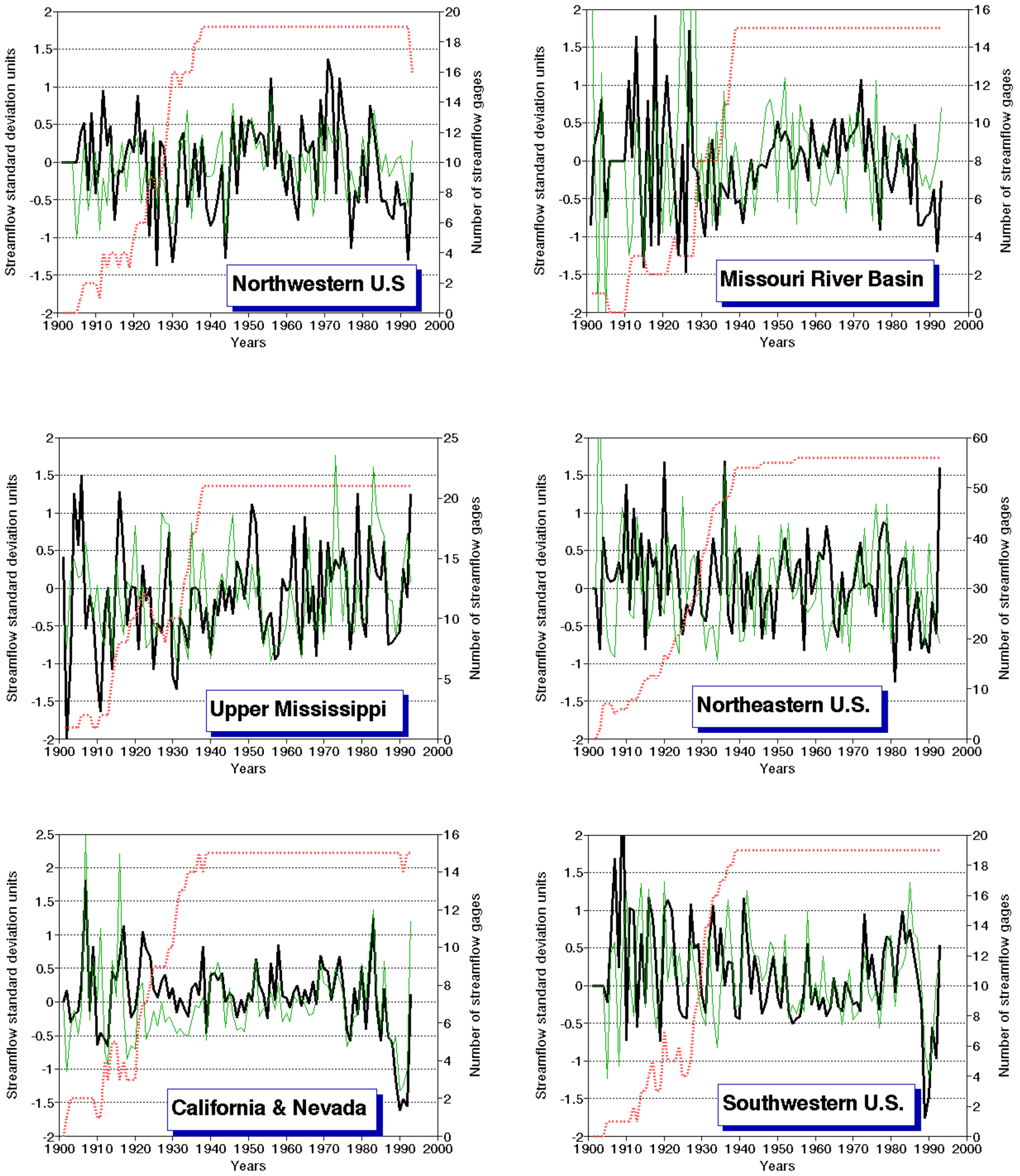

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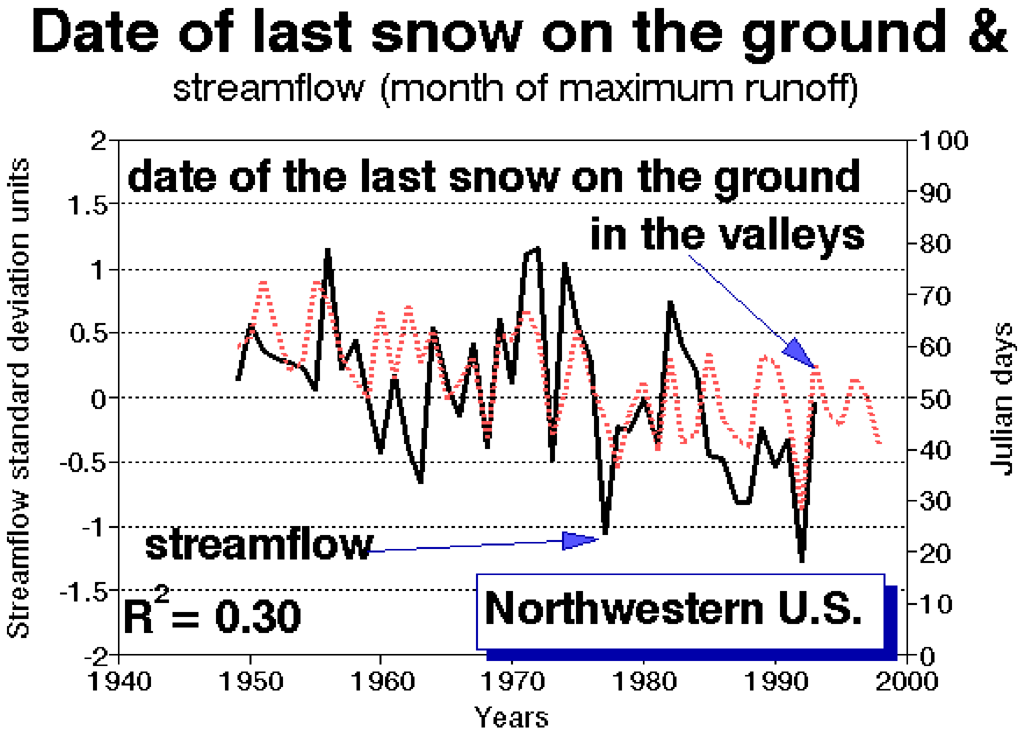

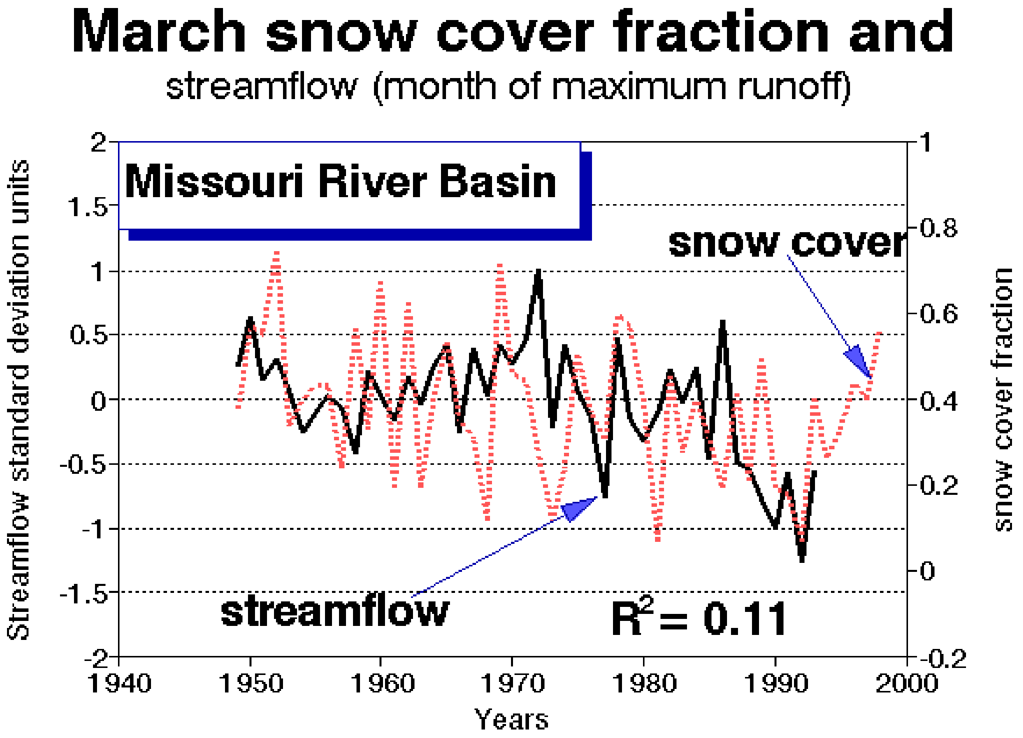

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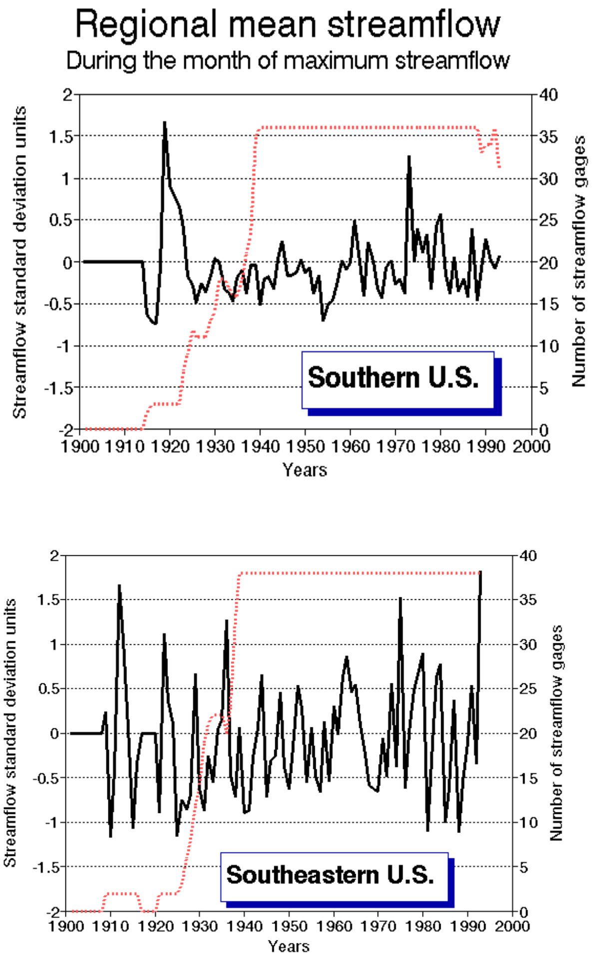

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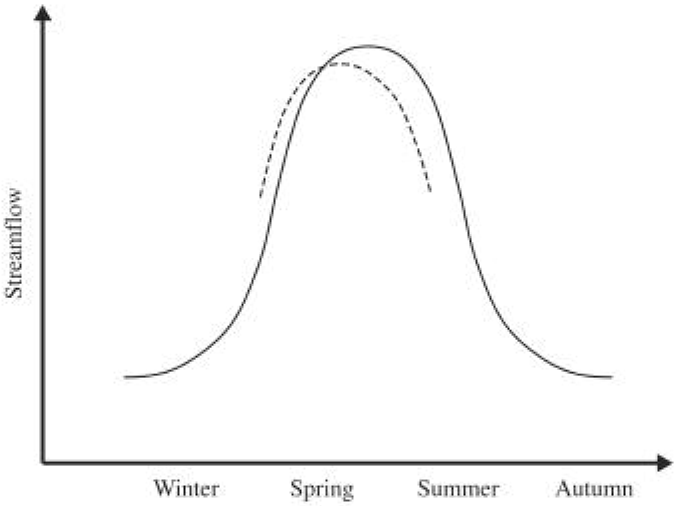

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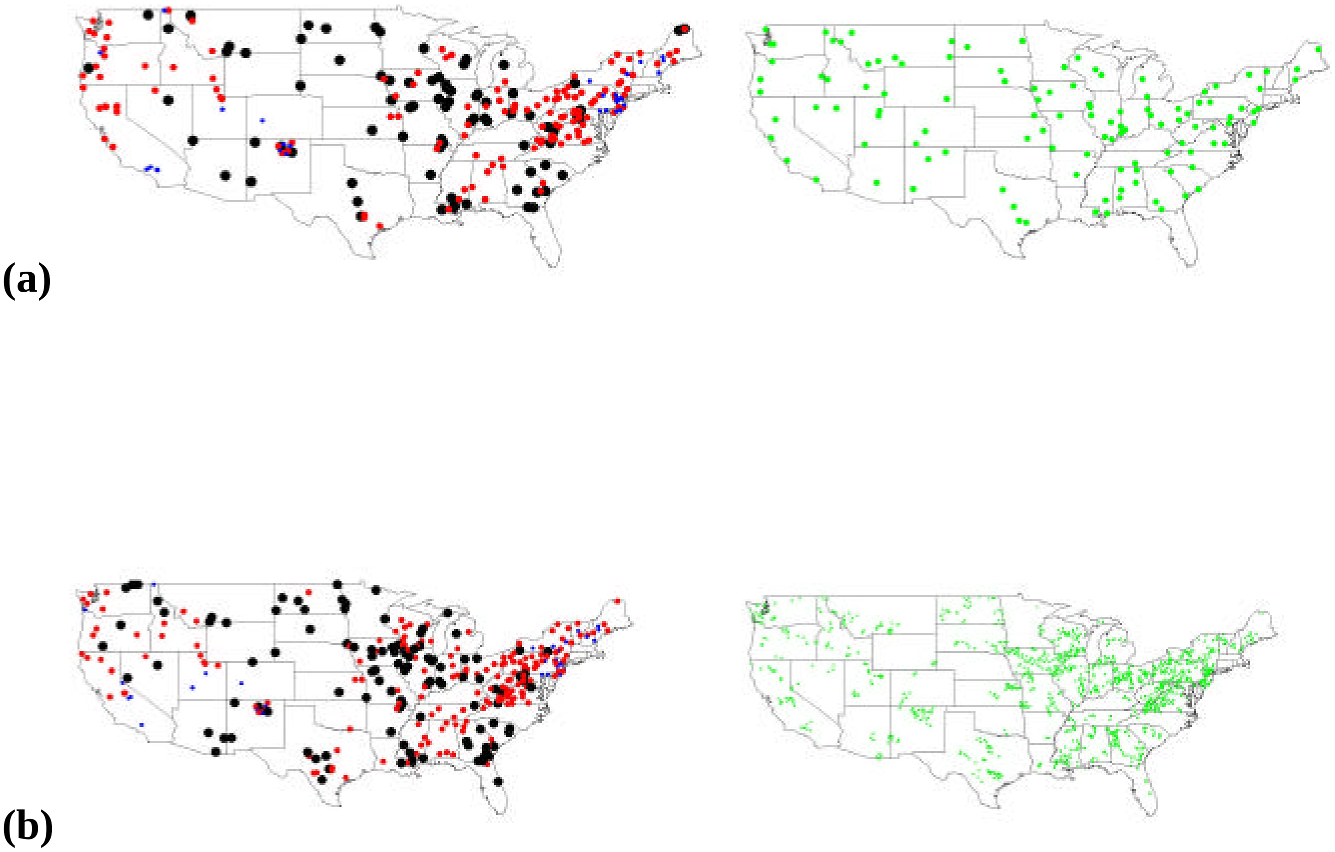

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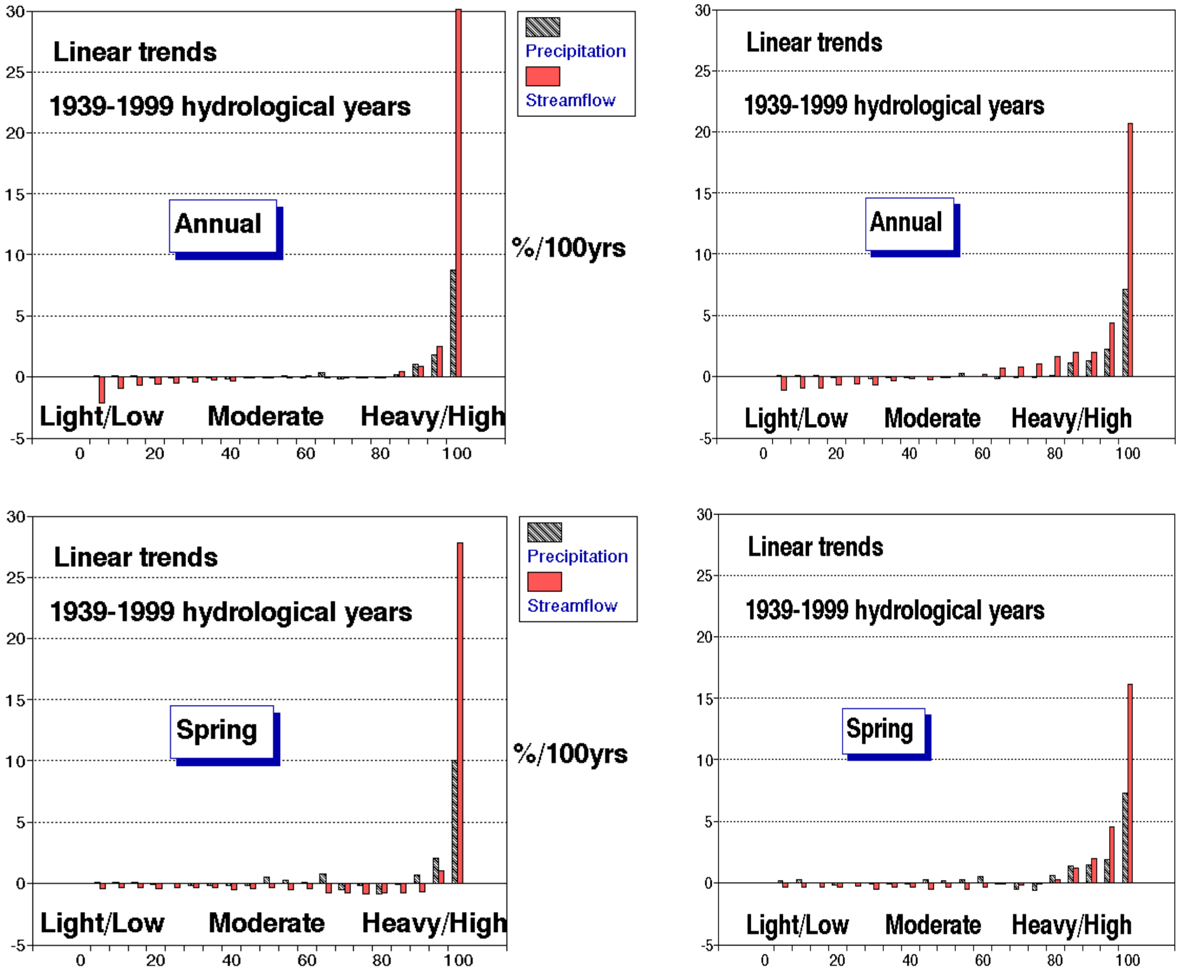
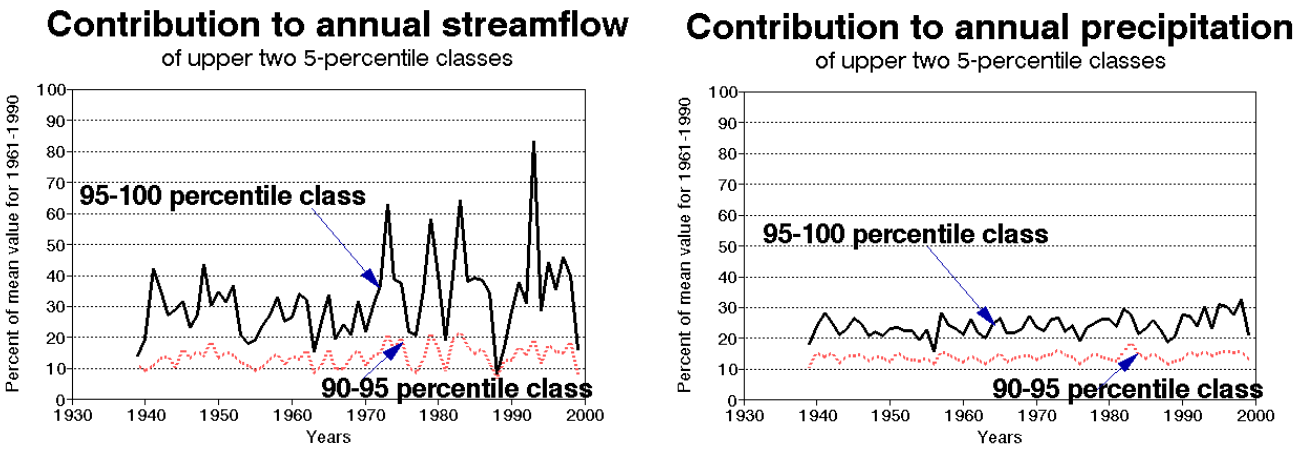


A. Percentiles distribution for each month   Percentiles distribution for annual events



B.

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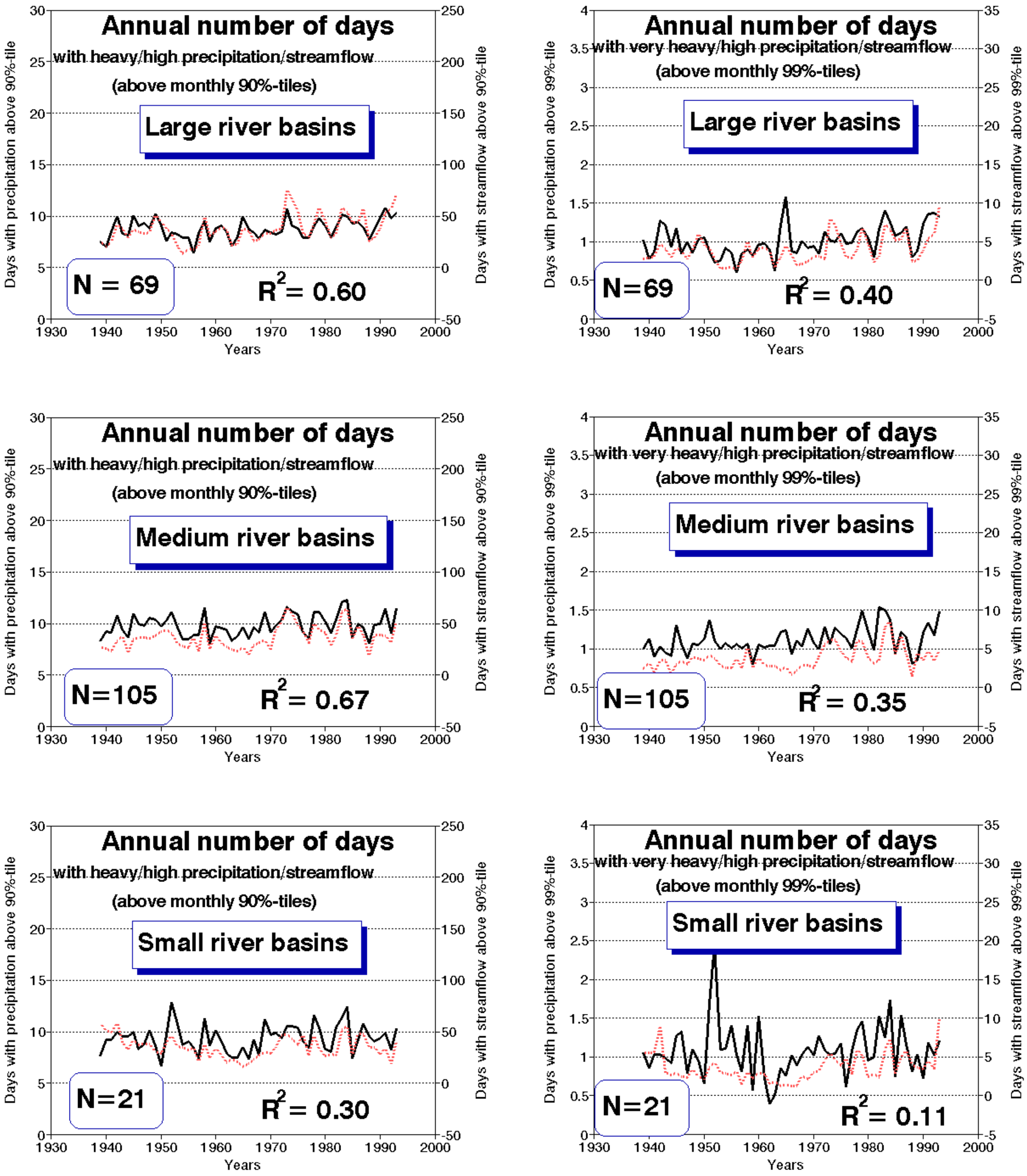

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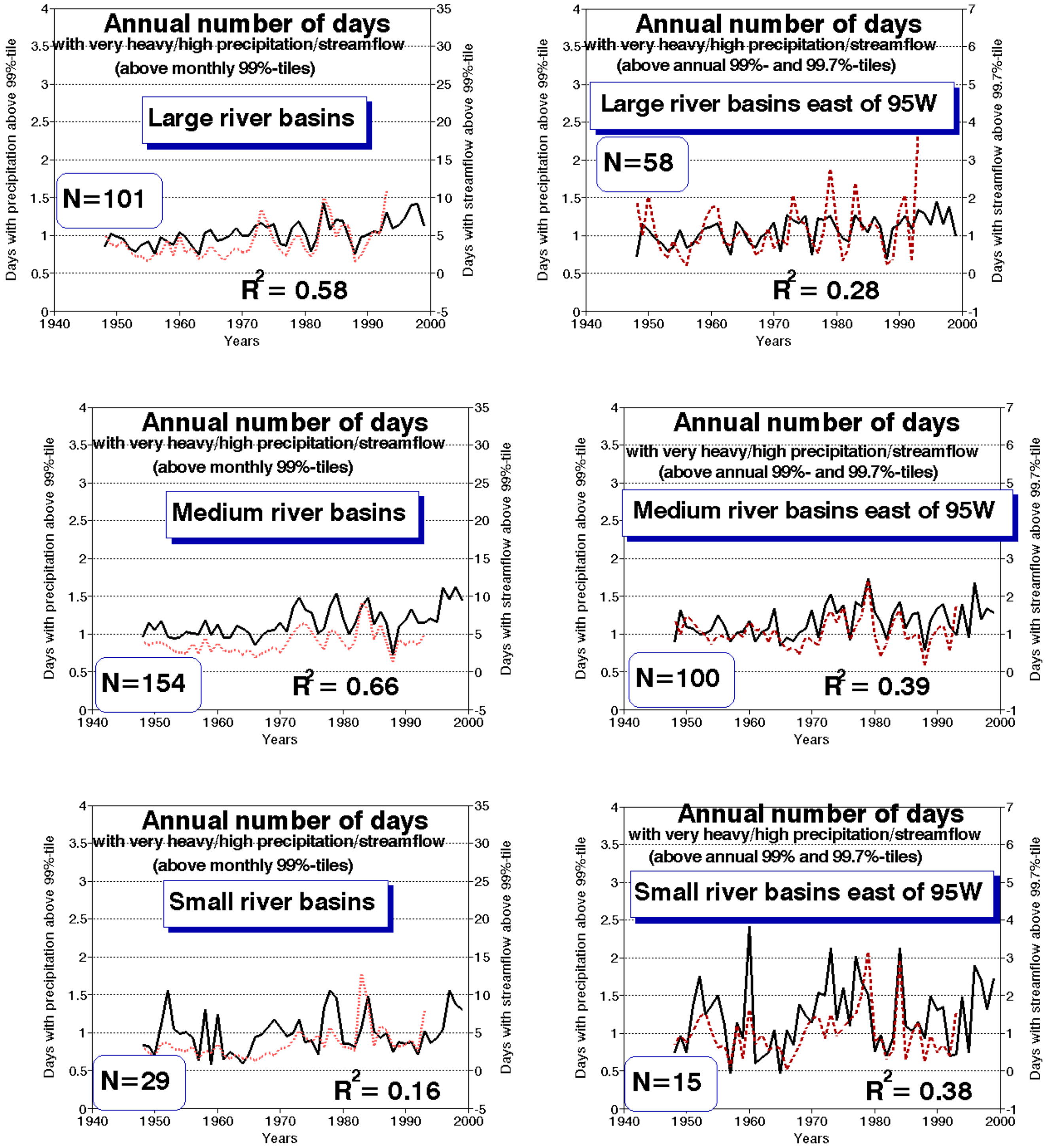

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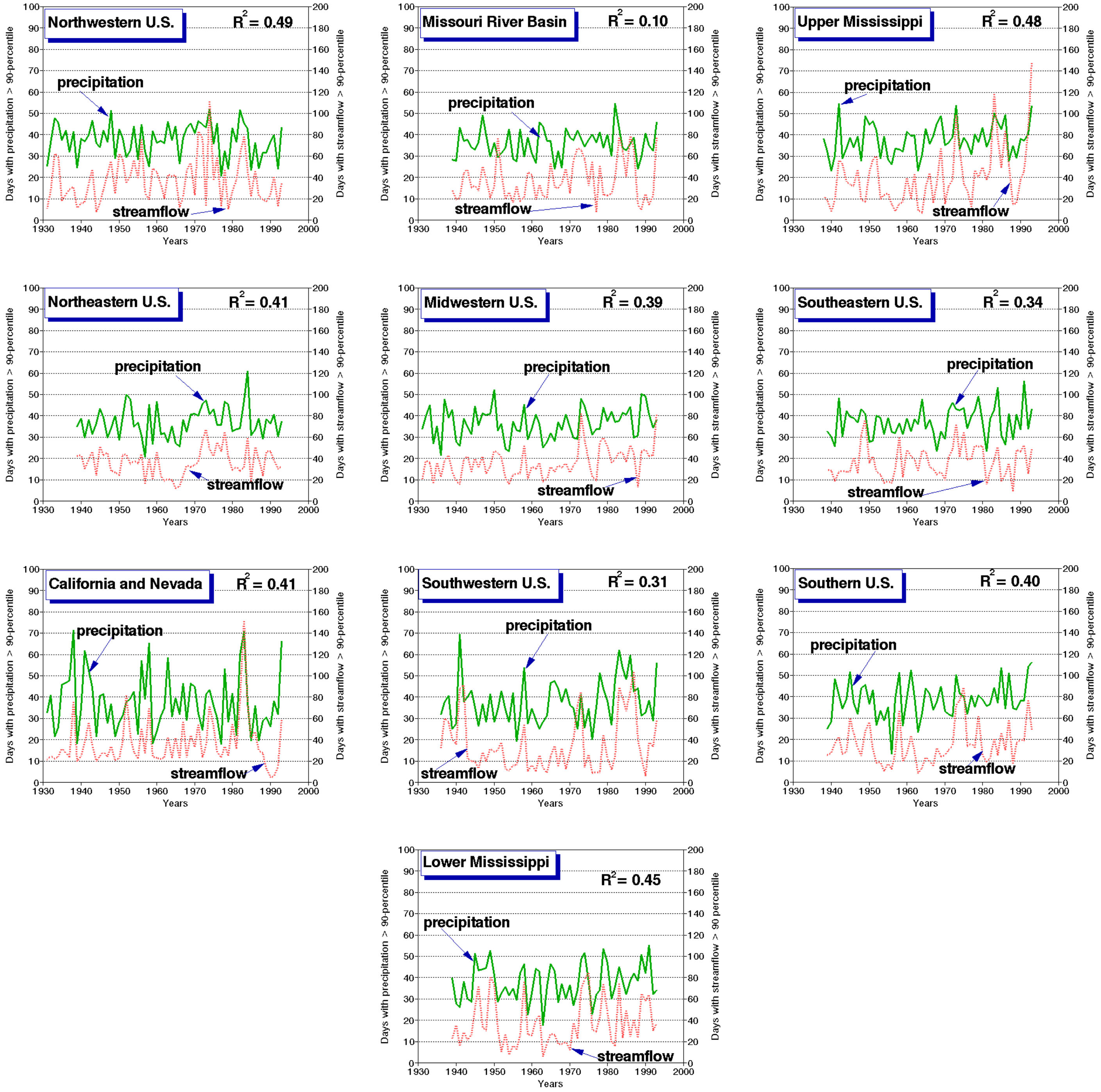

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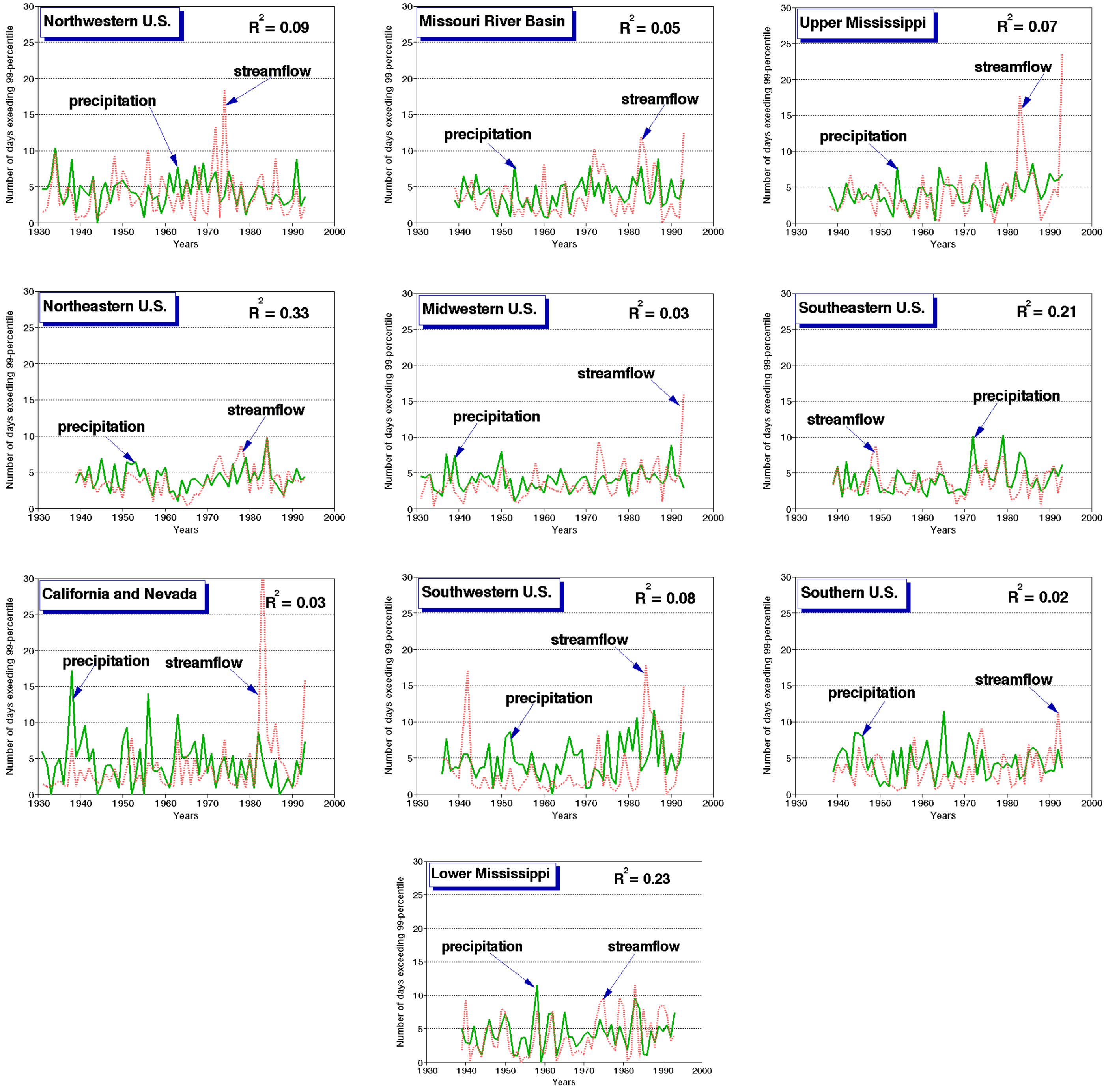
Figure 20. Same, as Fig. 19 but for the 95th percentile.



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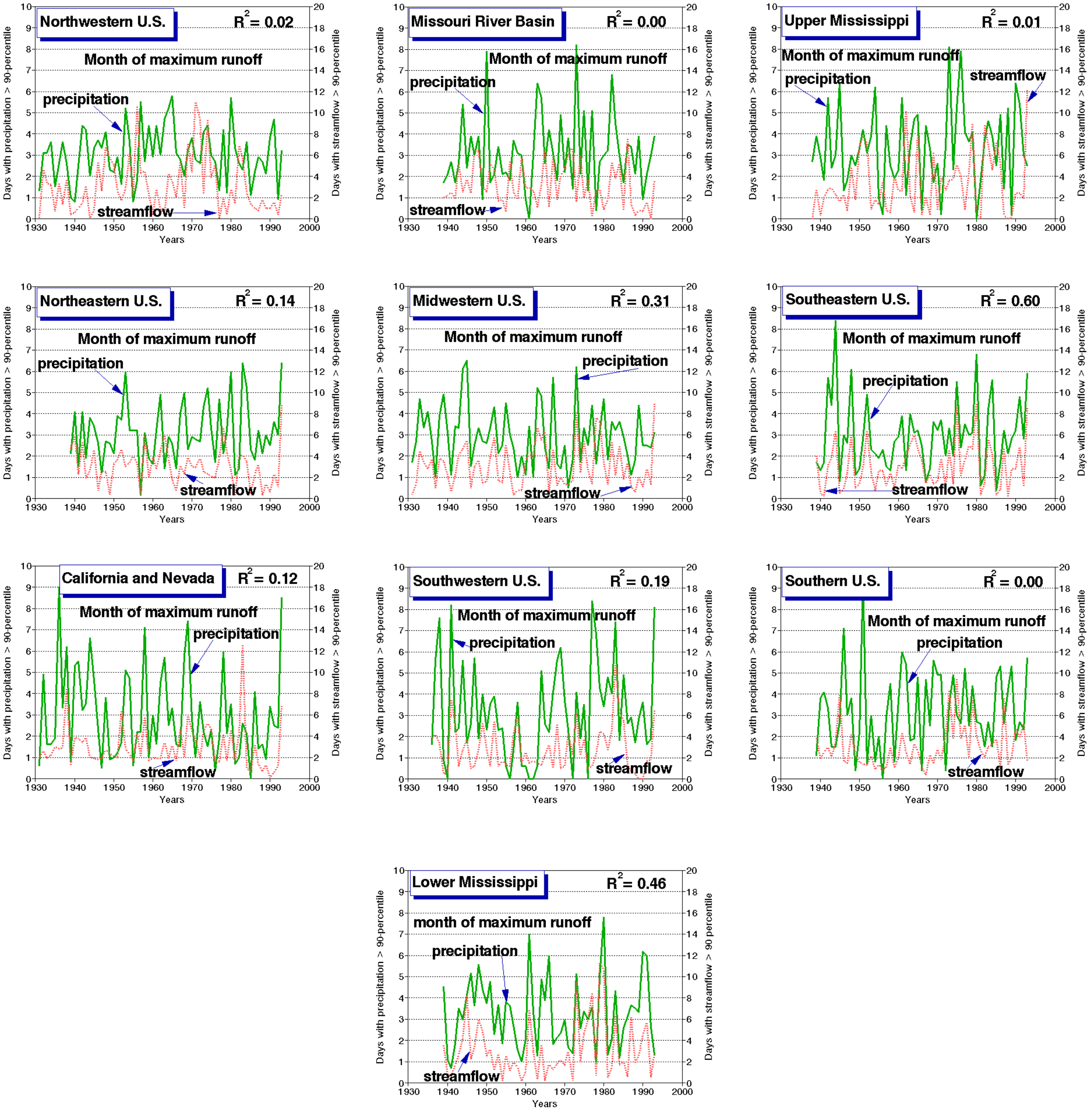

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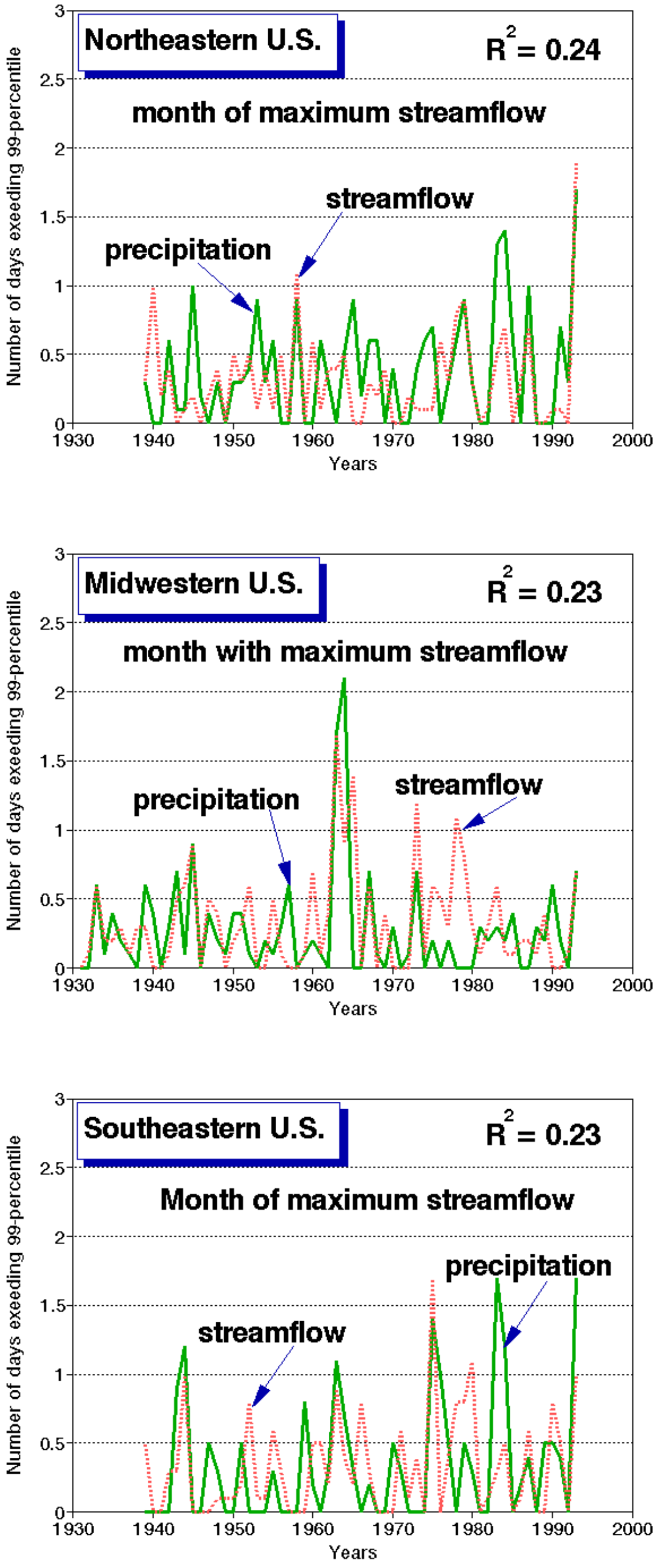

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