

Contemporary Changes of the Hydrological Cycle over the Contiguous United States: Trends Derived from In Situ Observations

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(Manuscript received 2 May 2003, in final form 15 October 2003)

ABSTRACT

Over the contiguous United States, precipitation, temperature, streamflow, and heavy and very heavy precipitation have increased during the twentieth century. In the east, high streamflow has increased as well. Soil wetness (as described by the Keetch–Byram Drought index) has increased over the northern and eastern regions of the United States, but in the southwestern quadrant of the country soil dryness has increased, making the region more susceptible to forest fires. In addition to these changes during the past 50 yr, increases in evaporation, near-surface humidity, total cloud cover, and low stratiform and cumulonimbus clouds have been observed. Snow cover has diminished earlier in the year in the west, and a decrease in near-surface wind speed has also occurred in many areas. Much of the increase in heavy and very heavy precipitation has occurred during the past three decades.

1. Introduction

This paper summarizes our knowledge about contemporary changes of the various components of the surface hydrological cycle over the contiguous United States. Contemporary global climate models (GCMs) have simulated *global* temperature increases related to changes in the chemical composition of the atmosphere more or less accurately as well as some large-scale general features associated with this increase. The same GCMs are inconclusive and often contradict each other when simulating important aspects of regional climate. For this reason, it is particularly important to monitor and document observed regional trends. These trends will be an important guide in future decades as related to regional- and global-scale forcings. Of course, some of the “observed” regional changes, being a manifestation of natural variability, could be unrelated to these forcings.

During the past 100 yr, the climate of the United States has been well recorded. This allows us to reproduce here a more detailed picture of climatic changes for the twentieth century compared to many other parts of the world. While presenting this picture we caution the reader against extrapolation to future changes. Not all tendencies that have been quantified for the past 50 or 100 yr will continue. Furthermore, the global near-

surface air temperature increase that has occurred in the past century is approaching levels not observed during the past several hundred years (Houghton et al. 2001, chapter 2), and regional “surprises” are increasingly possible in the extremely complex, nonlinear earth climatic system.

We primarily use our publications, conference presentations, and the extensive NCDC data archive to analyze changes in the hydrological cycle. For some elements, particularly temperature, snow cover, cloudiness, and atmospheric humidity, the in situ surface observations can be blended with satellite and rawinsonde observations that cover the last few decades (e.g., Robinson et al. 1993; Houghton et al. 2001, chapter 2). The major focus of this paper, however, will be on the long-term in situ observations, with special emphasis on very heavy precipitation. The term “nationwide” is used occasionally to characterize the conterminous United States only.

2. Data used

The digital archive of the U.S. cooperative network (NCDC 2003) contains about 8000 stations with daily records of precipitation, minimum and maximum temperatures (present in most locations), snowfall, snow depth, pan evaporation, and daily weather occurrence information (at some stations). For the study of long-term changes in the hydrological cycle over the conterminous United States, we selected ~6000 stations with sufficient daily records during the reference period

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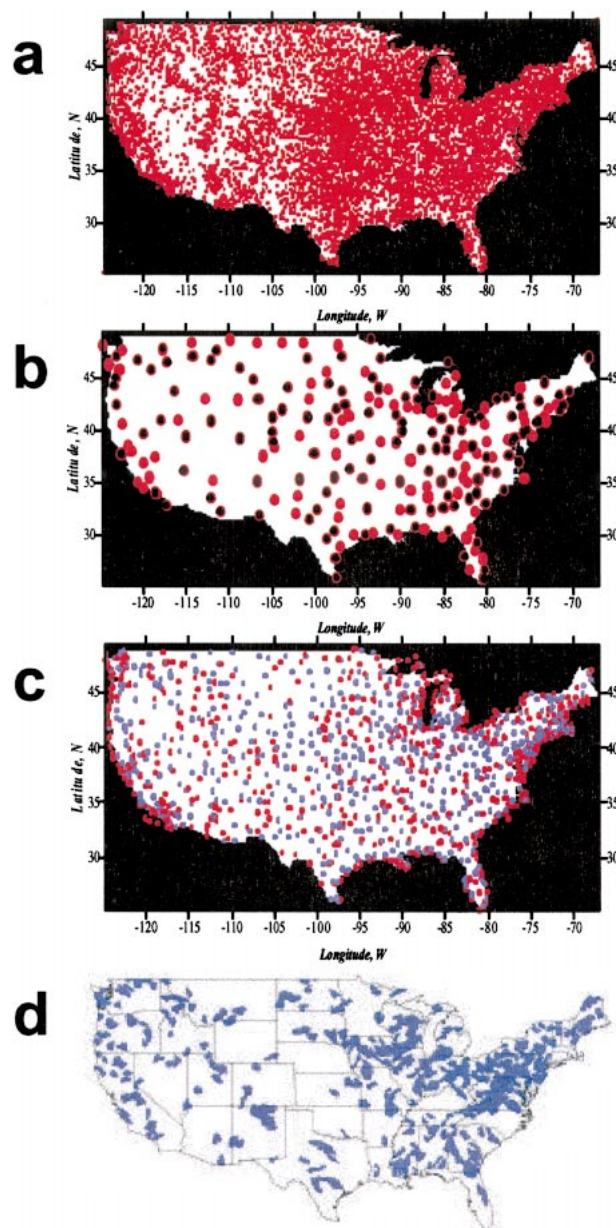


FIG. 1. Networks used in this study. (a) Cooperative precipitation network. Criteria for station selection included at least 25 yr of valid digitized daily data during the 1961–90 period. There are 5881 stations that satisfy this criterion. (b) First-order synoptic stations. Stations marked with black dots in the center represent a subset of the sites with serially complete cloud-type records for the period from 1952 to 1992 used to construct Figs. 20 and 22. (c) Synoptic stations over the contiguous United States with homogenized hourly wind information (Groisman and Barker 2002). Blue dots indicate the ASOS stations. (d) River basins covered by the set of long-term streamflow gauges (Lins and Slack 1999; 19.3% of the contiguous United States).

of 1961–90. Criteria for station selection included at least 25 yr (or 83%) of valid digitized daily data during the 1961–90 period. There are 5881 stations that satisfy this criterion (Fig. 1a). Reference periods are required

in the area averaging used to generalize our results within regions (cf. Groisman et al. 2001a,c) and are used to account for missing values in the long-term station records. Although the number of stations with available data is greatest during the past 50 yr, a significant improvement in the data coverage for the pre-1948 period has been achieved in the past 2 yr through an ongoing effort to digitize early records by the National Climatic Data Center's Climate Data Modernization Program (NCDC 2002; Groisman et al. 2002b; Fig. 2). Figure 2 shows the data availability for long-term daily precipitation time series 2 yr ago (Groisman et al. 2001a,c) and now. Now stations with at least 25 yr of valid digitized daily precipitation in 1961–90 that are also available 50% of the time during the 1921–30 period cover most of the country. Two years ago only the data for Midwestern states were available for analyses. Furthermore, now we have more than 1000 stations with digitized daily precipitation data for the first decade of the twentieth century (Fig. 2). This advance significantly improves our ability to assess century-long changes in characteristics of the atmospheric hydrological cycle that have long return periods *and* small spatial extent (in particular, frequencies of very heavy and extreme precipitation events). Using the same requirement, that is, 83% valid daily data during the 1961–90 period, we selected for our analyses a dataset of approximately 4200 cooperative stations for temperature and snow depth. For conclusions about mean monthly and annual temperature, we used a subset of high quality long-term cooperative stations; the U.S. Historical Climatology Network (USHCN) of 1221 stations (Easterling et al. 1996) as length scale decay is large for monthly and annual temperature anomalies. Therefore, the conclusions based on this subset are representative for the country.

Several other important meteorological elements (humidity, cloudiness, atmospheric pressure, and wind speed) are available only at synoptic airport stations. Most of the hourly digital information from the approximately 250 major U.S. airports (Fig. 1b) starts around 1950. Changes in observation practice and instrumentation make it difficult to use this network for some elements like cloud amount and precipitation for climate change analyses. For example, cloudiness information since the early 1990s became incompatible with previous observations after implementation of the Automatic Surface Observation System (ASOS; Karl et al. 1993; Sun et al. 2001). We also use about 1300 stations with homogenized near-surface wind (Groisman and Barker 2002) to assess the change in 10-m winds (Fig. 1c).

Results for streamflow described in this paper are based on the same daily dataset that was used by Groisman et al. (2001a,c) but updated through September 2003. This dataset represents an update of long-term homogeneous river gauge data used by Lins and Slack (1999) that, in turn, originated from the U.S. Geological

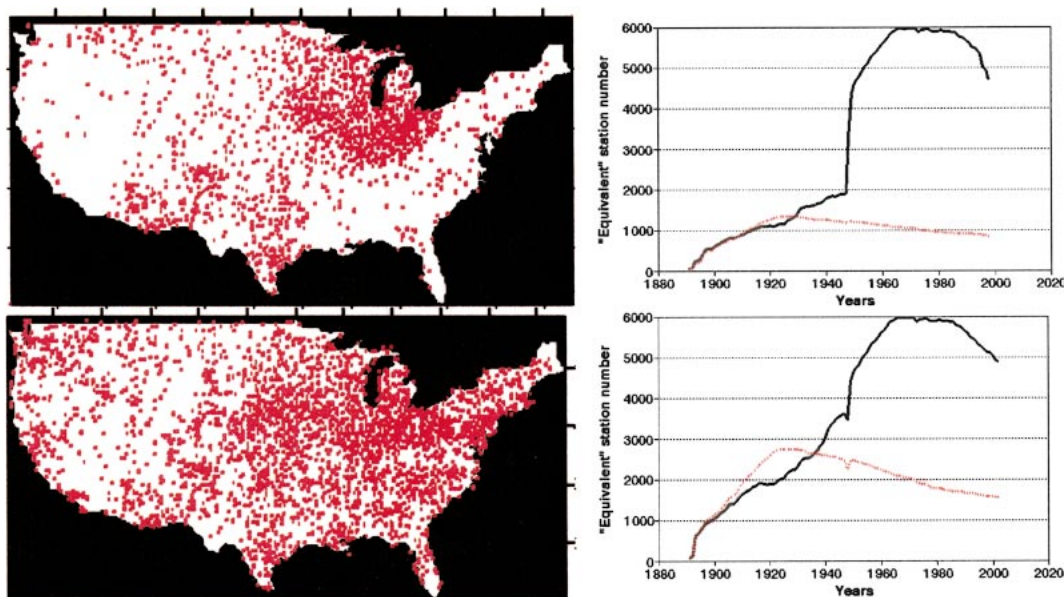


FIG. 2. Data availability for long-term daily precipitation time series in (top) 2001 (Groisman et al 2001a,c) and (bottom) 2003. Both maps show stations with at least 25 yr of valid digitized daily precipitation in 1961–90 that are also available 50% of the time during the 1921–30 period. Each plot shows data availability at the stations that have 83% of valid daily data during the 1961–90 period (black lines) and 1921–30 period (red dotted lines).

Survey (USGS) Hydro-Climatic Data Network (Slack and Landwehr 1992). The spatial distribution of these basins is shown in Fig. 1d.

3. Approach

a. Area averaging

In each location, spatial variability of each observed meteorological variable has a strong microclimatic component that may not be of interest when analyzing systematic changes over the large region. Area averaging is an essential tool to reduce/remove a significant fraction of this variability and increase the signal-to-noise ratio. We used this tool liberally in our quest for trends in climatological variables related to the hydrological cycle over the conterminous United States. It is exceptionally rare that a signal is so strong (and the variability of the climatological variable is so low) that the point measurements give statistically significant trends en masse. Temperature, especially annual temperature over the northern half of the country, is among these exceptions. Other climatological characteristics are highly variable, and the characteristics of rare events such as “heavy” and “very heavy” precipitation are variable at the highest degree. It is unreasonable to expect a discovery of statistically significant trends in such point measurements, and it would be equally unreasonable to claim the failure of such an attempt as a justification of the “no change” hypothesis. For example, in several recent studies (Lins and Slack 1999; Douglas et al. 2000; McCabe and Wolock 2002), trends in minimum and

maximum daily streamflow at individual gauge locations over the contiguous United States were examined. Each of these studies has reported significant positive trends in low streamflow time series (the variable that has a relatively small interannual variability). However, a significant number of individual locations with statistically significant trends in maximum flow (the variable that has an enormous interannual variability) were not found. Obviously, the signal-to-noise ratio for maximum annual streamflow at each location was prohibitively high to allow statistically significant trends to be revealed. However, when the area-averaging routine of the variable reveals a trend, its interpretation has to be put into perspective. For example, we can say that “on average” a particular trend has been observed but cannot claim the same for each location within the region in question. Furthermore, area averaging can be counterproductive and even misleading when changes of opposite signs have occurred within the region. When we anticipated such a possibility (e.g., southeastern coastal zone subjected to hurricane influence), we created an additional partition and considered these regions separately. The regional averaging technique employed throughout this paper is described in appendix A.

b. Trend assessment

In this paper, we present time series of different variables associated with the hydrological cycle over the conterminous United States and assess their trends (when present) for the period of greatest observational

measurements. These periods have been usually selected as the maximum period when “sufficient” amounts of digital data representative for regional averages are available (Kagan 1997). For variables with a significant spatial correlation (e.g., seasonal temperature) the “sufficiency” thresholds (the requirements on the number and spatial distribution of stations that can reliably characterize the area-averaged value of the element) are more liberal than those for variables with high spatial variability such as thunderstorm activity. The same network can be “sufficient” for presenting the results on regional seasonal precipitation but inadequate for presenting the results on area-averaged frequency of “extreme” daily precipitation (which we define throughout this paper as a rare event with daily total exceeding the upper 99.9th percentile of precipitation events at a given location). In the second case, two sparse networks in the same region can give opposite results. When possible, we performed “frozen” network experiments (i.e., repeated our analyses for selected networks of different density) to ensure that our results are robust and present them only for periods with a “sufficient” amount of spatial data coverage. For example, when presenting results for daily precipitation, we frequently use 1908 as a starting point. This is the year when the nationwide number of $1^\circ \times 1^\circ$ grid cells with valid daily precipitation data first exceeded 600 (from a maximum possible 886). August 1948 was the starting date when digital media were first introduced for U.S. meteorological archiving. While substantial efforts have been made recently to digitize the pre-1948 data (Fig. 2), the number of synoptic digitized reports for the first half of the twentieth century is still insufficient for century-long assessment of humidity, cloudiness, severe weather, and other synoptic information with daily and/or subdaily time-scale resolution. Changes of observational practice and instrumentation (in particular, the automation in the early 1990s) also restrict periods for which homogeneous time series of some variables (e.g., cloudiness) can be constructed and their climatic trends assessed (Sun et al. 2001). Care also was taken to avoid the presentation of trend results that can be unduly affected by the starting/ending points of the time series.

We present numerous time series of different variables, but not all of these variables show systematic changes (trends) during the period under consideration. We nevertheless chose to include the variables that are essential components of the hydrological cycle. In these cases the time series were presented to illustrate their interannual variability in a given region.

We have performed trend analyses on every element and period and have taken particular care to discuss the significance of the trends that we found. When the figures and discussion refer to only part of the regions and/or seasons, the reader should assume that for other regions/seasons we did not find the trends statistically significant. When we explicitly use (in the figure caption, text, or accompanied table) terms “substantial” and/or “signif-

icant” when attributing trend estimates, this indicates that these trends were found to be statistically significant at the 0.05 level or higher. Otherwise, when the maps and/or time series are shown without explicit statements about statistical significance, no statistical significance (at the level of 0.05) should be assumed. Methods used for trend analysis and evaluation of its statistical significance are described in appendix B.

We present mostly linear trend estimates throughout this article. In a few cases, when significant nonlinearity was detected, we point it out explicitly. In most cases we present the actual time series, which allows the reader to judge the form of systematic trends revealed. We did not focus on the linearity of the changes and used (in addition to the linear trend assessment) a non-parametric test to check for a monotonic trend of increase/decrease of the time series. Once a trend has been discovered, the next question is how to characterize it. We chose to use the *mean rate of changes*. Linear trend estimate is an essential characteristic in this case. Throughout this paper, we normalized the trend estimates to a 100-yr period regardless of the actual length of the time series.

c. *New versus known/published results*

Every result presented in this paper has been previously presented at numerous international conferences during the past three years (B. E. Gleason et al. 2002, unpublished manuscript; Groisman 2002; Groisman and Barker 2002; Groisman et al. 2001b,c, 2002a,b, 2003b,c). Results related to mean monthly/seasonal/annual temperature and precipitation have been updated and presented to preserve the complete picture. This information has been made publicly available and can be viewed/downloaded at the National Climatic Data Center Web site (www.ncdc.noaa.gov). We present updated results based on more complete information (cf. Fig. 2) on heavy precipitation and snow cover published earlier by Groisman et al. (2001a). However, we could not substantially update our results (Sun et al. 2000, 2001; Groisman et al. 2001c) related to cloudiness changes because automation has made most of the synoptic information on a suite of cloudiness characteristics incompatible with previous man-made observations since the early 1990s (Sun et al. 2001).

4. Trends

a. *Temperature*

Changes in the U.S. nationwide mean surface air temperature during the twentieth century are not monotonic (Fig. 3). The warming during the first and last thirds of the century was interrupted by a cooling period in the middle of the century. Figure 3 also shows the Northern Hemispheric surface air temperature (Lugina et al. 2003). The trends and low-frequency variability in both

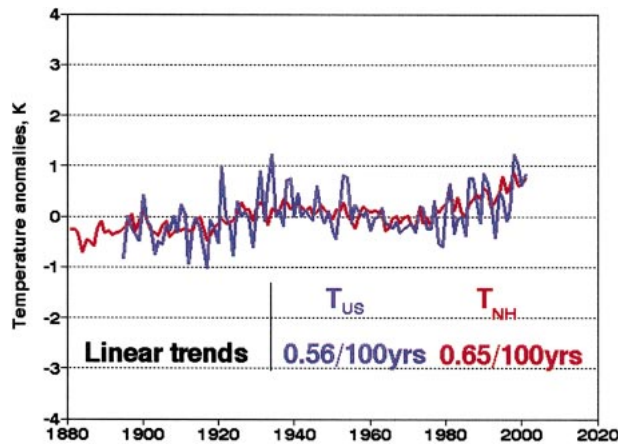


FIG. 3. Annual area-averaged temperature over the contiguous United States (1895–2002) based on the USHCN (T_{US} ; blue line) and over the Northern Hemisphere (1881–2002) (Lugina et al. 2003; T_{NH} ; red line). (Sources: <http://www.ncdc.noaa.gov/oa/climate/research/2002/ann/us-summary.html#Atemp> and <http://cdiac.esd.ornl.gov/trends/temp/lugina/data.html>.)

time series are remarkably similar. Of course, station temperature data from the conterminous United States were used to derive the hemispheric temperature, but the region constitutes only about 3% of the hemispheric area. After detrending and “whitening” (Kendall and Stuart 1967), these time series still share about 10% of common variance and are significantly correlated at the 0.001 level. Changes of the global surface air temperature on decadal and longer time scales are currently reasonably well reproduced by modern GCMs with external forcing related to changes in chemical and aerosol composition of the atmosphere (Houghton et al. 2001). Very recent studies have shown that the most advanced GCMs can do the same on a “continental” spatial scale including the size of the United States (F. Zwiers 2003, personal communication). The close resemblance of the hemispheric and nationwide low-frequency temperature variations during the past century indicate that the general causes of these variations could be similar.

Geographically, the most significant century-long increase in surface air temperatures occurred in the northern and western parts of the country (where even gridded annual temperature trends are statistically significant at the 0.05 level), while some temperature decreases occurred in the southeast (Fig. 4). Karl et al. (1991) found significant asymmetry in warming over the United States as well as over other parts of the extratropics: minimum temperature increased more rapidly than maximum temperature, and in many cases much or even the entire warming trend was attributed to the nighttime warming. Over the conterminous United States, a substantial increase in minimum temperatures has been documented in winter (not shown) and spring, with the biggest changes confined to the northwestern quadrant of the country and to the past 50 yr (Figs. 4 and 5). During the past 50 yr, summer minimum temperatures

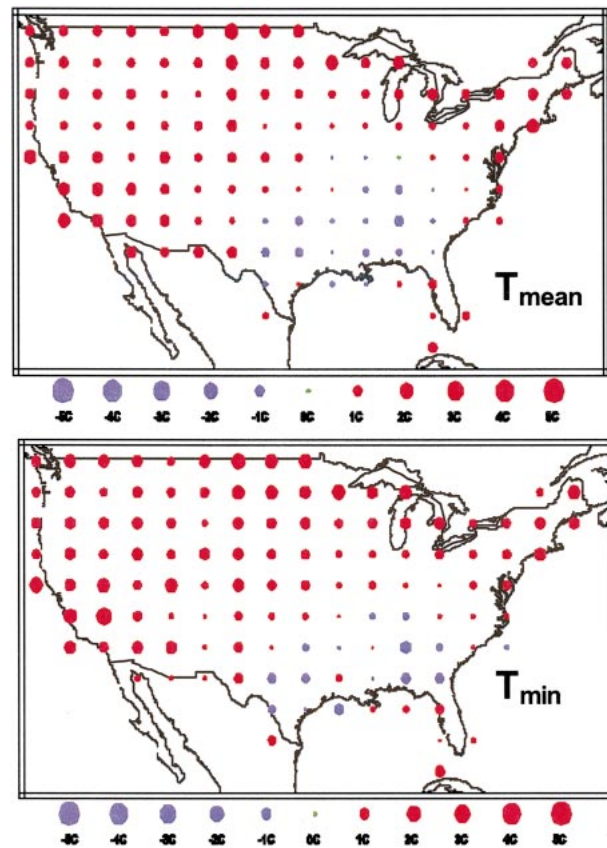


FIG. 4. (top) Annual mean (T_{mean}) and (bottom) minimum (T_{min}) temperature trends for the past century (1900–2002). Individual trends from USHCN stations have been area averaged within a $2.5^\circ \times 3.5^\circ$ grid. Red dots indicate increasing and blue dots decreasing trends. The dot areas are proportional to the trend values [$^\circ\text{C} (100 \text{ yr})^{-1}$], with the largest in the legend equal to $\pm 5^\circ\text{C} (100 \text{ yr})^{-1}$.

have also increased nationwide except for Texas and Oklahoma (Fig. 5). A substantial nationwide increase in maximum temperatures during the past 50 yr was observed only in spring.

b. Precipitation

The precipitation record is characterized by much more spatial and temporal variability than temperature. Consequently, trends constitute a small fraction of this variability compared to temperature, and precipitation anomalies in each year usually are much greater than any trend at each location. However, changes in precipitation affect the surface water balance (soil moisture, runoff, and lake levels), and it is important to know how these trends are manifested in terms of intraannual distribution and intensity. It has been shown that with an increase or decrease of total precipitation, disproportionate changes occur in the upper end of the precipitation frequency distribution (Karl and Knight 1998; Groisman et al. 1999, 2001a; Kunkel et al. 1999; Eas-

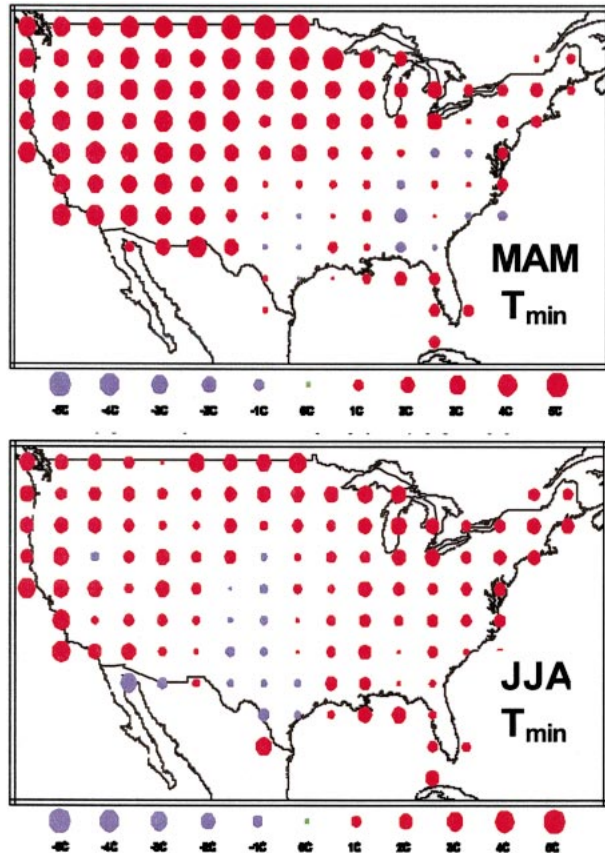


FIG. 5. (top) Spring (Mar–Apr–May) and (bottom) summer (Jun–Jul–Aug) minimum temperature trends for the past 53 yr (1950–2002) based on the USHCN. Red dots indicate increasing and blue dots decreasing trends. The dot areas are proportional to the trend values [$^{\circ}\text{C} (100 \text{ yr})^{-1}$], with the largest in the legend equal to $\pm 5^{\circ}\text{C} (100 \text{ yr})^{-1}$.

terling et al. 2000; Houghton et al. 2001; Semenov and Bengtsson 2002; Kunkel 2003). Therefore, in this section we present estimates of changes in *mean* and *very heavy* precipitation separately.

TABLE 1. Area-averaged annual daily precipitation thresholds, P , for the 90th–95th (heavy), 99th–99.7th (very heavy), and 99.9th (extreme) percentile precipitation events in different regions of the contiguous United States. Note that at each specific location the threshold precipitation value may be different. The return period for such events varies depending upon the frequency of days with measurable precipitation and constitutes, e.g., from 3 to 5 yr for precipitation events above the 99.7th percentile. Region number corresponds to those shown in Fig. 8.

Region number	Subregion	P (mm)				
		90	95	99	99.7	99.9
1	Northwest	15	20	35	45	55
2	Missouri River basin	15	20	35	50	65
3	Upper Mississippi	20	25	45	65	80
4	Northeast	20	30	50	65	80
5	California and Nevada	20	30	50	65	80
6	Southwest	15	20	35	45	55
7	South	30	40	75	105	130
8	Midwest	25	35	60	80	100
9	Southeast	30	45	75	105	130
	48-states average	20	30	50	70	90

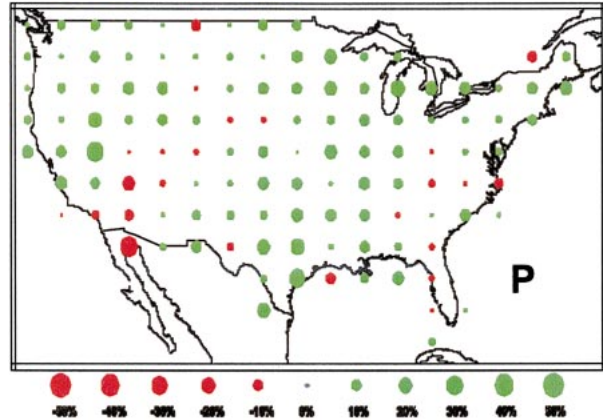


FIG. 6. Linear trends [$\% (100 \text{ yr})^{-1}$] of annual precipitation (P ; 1900–2002) over the contiguous United States. Individual trends from 1221 USHCN stations (Easterling et al. 1996) have been area averaged within a $2.5^{\circ} \times 3.5^{\circ}$ grid. Green dots indicate increasing and brown dots decreasing trends. Updated and reformatted from Groisman et al. (2001a).

1) MEAN PRECIPITATION

Nationwide time series of *mean precipitation* indicate significant interannual variability with two particularly noteworthy dry decades (1930s and 1950s), followed by relatively wet decades (1970–99) giving way to a century-long precipitation increase (cf. <http://www.ncdc.noaa.gov>).

Geographically, the increase varies and is absent over parts of the southeastern and southwestern United States (Fig. 6). The nationwide increase of 7% to 15% ($100 \text{ yr})^{-1}$ in seasonal precipitation is confined to spring, summer, and autumn (Karl and Knight 1998; Groisman et al. 2001a). Annually, the nationwide precipitation increase is 7% ($100 \text{ yr})^{-1}$ (see Table 2 below). We present updated (up to December 2002) estimates of trends in mean precipitation. The update is important because nationwide precipitation was below normal during the 1999–2002 period.

2) HEAVY AND VERY HEAVY PRECIPITATION

An analysis of *heavy and very heavy precipitation* requires the use of the densest network possible. Of course, an assessment of the longest time series available is necessary in order to increase the likelihood of detecting statistically significant changes in frequency of these rare events. Regional averaging is required to suppress small-scale variability due to the occurrence of convective storms. In our first analyses (Karl and Knight 1998; Groisman et al. 1999), we sometimes used absolute units as thresholds to characterize “heavy” and “very heavy” daily precipitation events (e.g., 50 or 100 mm). Below, we present results based on the frequency of occurrence of precipitation events in each location. We define, for example, “very heavy” as an event that is observed in not more than 1 of 100 (above the 99th percentile) or in not more than 3 of 1000 daily rain events (i.e., above the 99.7th percentile) at each location. This approach provides for more consistent assessment across diverse areas of the country related to infrequent (therefore potentially dangerous) events, but at the same time defining different local absolute thresholds for the definition of heavy and very heavy precipitation (Groisman et al. 2001a). Table 1 provides a typical threshold spread over the contiguous United States for various percentiles of annual 24-h rain event (loosely corresponding to heavy, very heavy, and extreme precipitation events throughout this paper).

Figure 7 shows changes in nationwide (conterminous United States) annual precipitation with a partition of daily rainfall into heavy (above the 95th percentile), very heavy (above the 99th percentile), and extreme (above the 99.9th percentile) events. Table 2 provides some statistical characteristics of the time series shown in this figure. Figure 7 and Table 2 indicate that, while the mean total precipitation increased, the heavy and very heavy precipitation increase was significantly greater, as was the proportion of the totals attributed to these events. Furthermore, a thorough analysis of these time series indicates that practically the entire nationwide increase in heavy and very heavy precipitation has occurred during the past three decades (Soil and Water Conservation Society 2003).

Regionally and seasonally, changes in very heavy precipitation vary significantly, and the magnitude of the trends is most notable in the eastern two-thirds of the country and primarily in the warm season when the most intense rainfall events typically occur (Fig. 8). In Fig. 8, regions are shaded where statistically significant trends in very heavy precipitation (above 99.7th percentiles) were documented for the 1908–2000 period (Groisman et al. 2002a,b). We updated these estimates

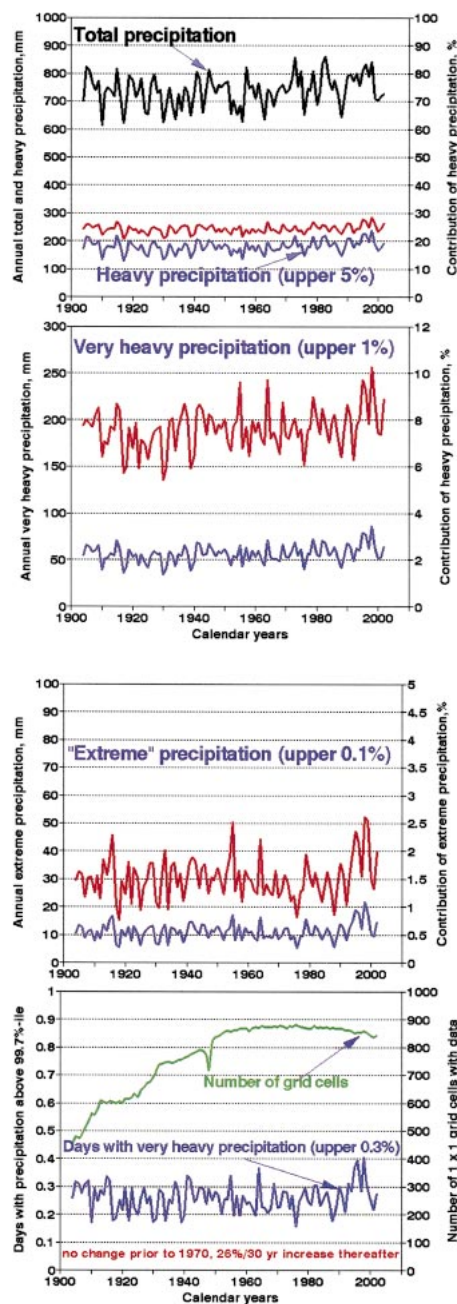


FIG. 7. Changes in total (black line), heavy, very heavy, and extreme (blue lines) precipitation over the conterminous United States and their contribution to annual totals (red lines). Update of results

of Groisman et al. (2001a,c; 2002a). All time series in the upper two panels have positive trends that are statistically significant at the 0.01 level or higher. Linear trends in total precipitation, upper 5%, and upper 1% of precipitation totals are 7%, 14%, and 20% (100 yr)⁻¹, respectively. The relative increase in the contribution of upper 5% and upper 1% of precipitation events to annual totals have increased by 7% and 13% (100 yr)⁻¹, respectively. Trends in the upper 0.1% precipitation and its contribution to annual totals are insignificant. The frequency of the days with daily precipitation events in the upper 0.3% (with an average nationwide return period of 3.6 yr) is shown in the lowest panel. It is increasing, but all this increase (statistically significant at the 0.05 level) has occurred in the past 30 yr. Number of 1° × 1° grid cells with valid station data shown in the lowest plot (and in the following graphs) is an important characteristic of the accuracy of area averaging. It was used throughout the study to control and display the level of representativeness of our results.

TABLE 2. Trends (1908–2002) of the annual national precipitation time series shown in Fig. 7. Asterisks (*) indicate statistically significant trends at the 0.05 or higher levels.

Characteristic	Mean value	Linear trend [% (100 yr) ⁻¹]	Explained variance (%)
Precipitation			
Total	750 mm	7*	7
Heavy, 95th percentile	200 mm	14*	9
Very heavy, 99th percentile	65 mm	20*	10
Extreme, 99.9th percentile	13 mm	21	4
Relative contribution to annual totals			
Heavy	26%	1.6*	9
Very heavy	8%	1.0*	13
Extreme	1.4%	0.2	2

and show the time series for three regions with significant trends in very heavy annual daily precipitation in Fig. 9. The regions encircled major agricultural areas of the central and eastern United States. All these trends are positive, and the update (which includes four relatively dry years, 1999–2002) has not changed the significance of these trends (Fig. 9).

In an attempt to evaluate the effects of very heavy precipitation on streamflow, we singled out a region where more than 80% of annual total precipitation falls in liquid form (the eastern and southern portions of the country, which is 67% of the contiguous United States). Additionally, we outlined a southeast coastal region where a significant contribution of the total annual precipitation is related to tropical storm rainfall (Groisman et al. 2001c). Within these three megaregions there was a general century-long increase in total precipitation and heavy precipitation (the upper 5% of rain events; Fig. 10). This type of analysis approach was first used by Karl and Knight (1998) and is now applied to approx-

imately 6000 stations for the period in each region that has a sufficient amount of long-term daily precipitation time series.

To illustrate what happens when percentiles are replaced with absolute thresholds (in this case 4 in. or 101.6 mm day⁻¹), we calculated century-long trends for the three regions shown in Fig. 10. While heavy precipitation (upper 10% of rain events) is increasing in the region “with >20% of total precipitation in frozen form” (Fig. 10), extremely rare events (above 101.6 mm, which on average occurs in this region once per 40 yr) cannot be captured or do not change appreciably over this region. At the same time the frequency of the “4 inches” has increased by ~30% during the past 100 yr over most of the contiguous United States outside of the “snowy” region. Table 3 also shows that the nationwide amount of precipitation that comes from “4 inches” has increased by 30% during the past century. In this table we show our previous results (top of Table 3A, taken from Groisman et al. 2001a) and the present

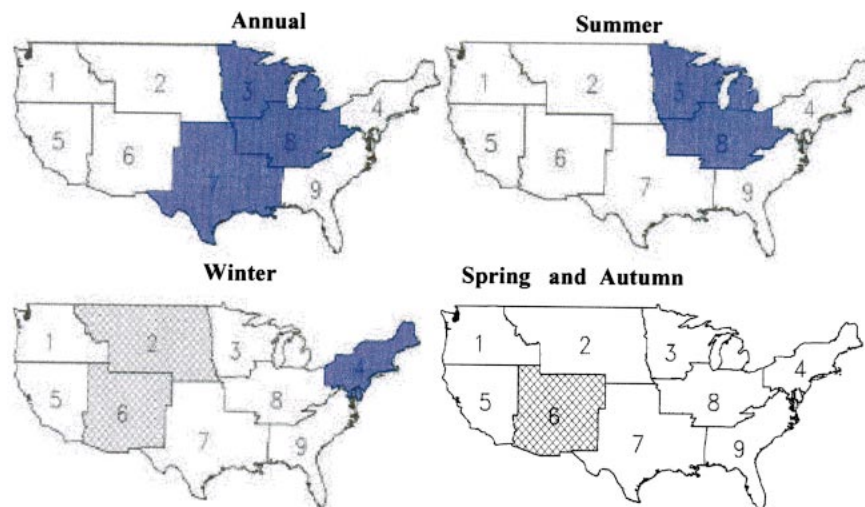


FIG. 8. Areas of significant trends in very heavy daily precipitation (above 99.7th percentiles) over the conterminous United States (1908–2000). Dark areas indicate increasing and hatched areas decreasing trends. Only trends that are statistically significant at the 0.05 significance level are shown. For seasonal precipitation, 99.7th percentile thresholds usually indicate daily rain events with a return period above 10 yr, while for annual precipitation it is in the range of 3–5 yr.

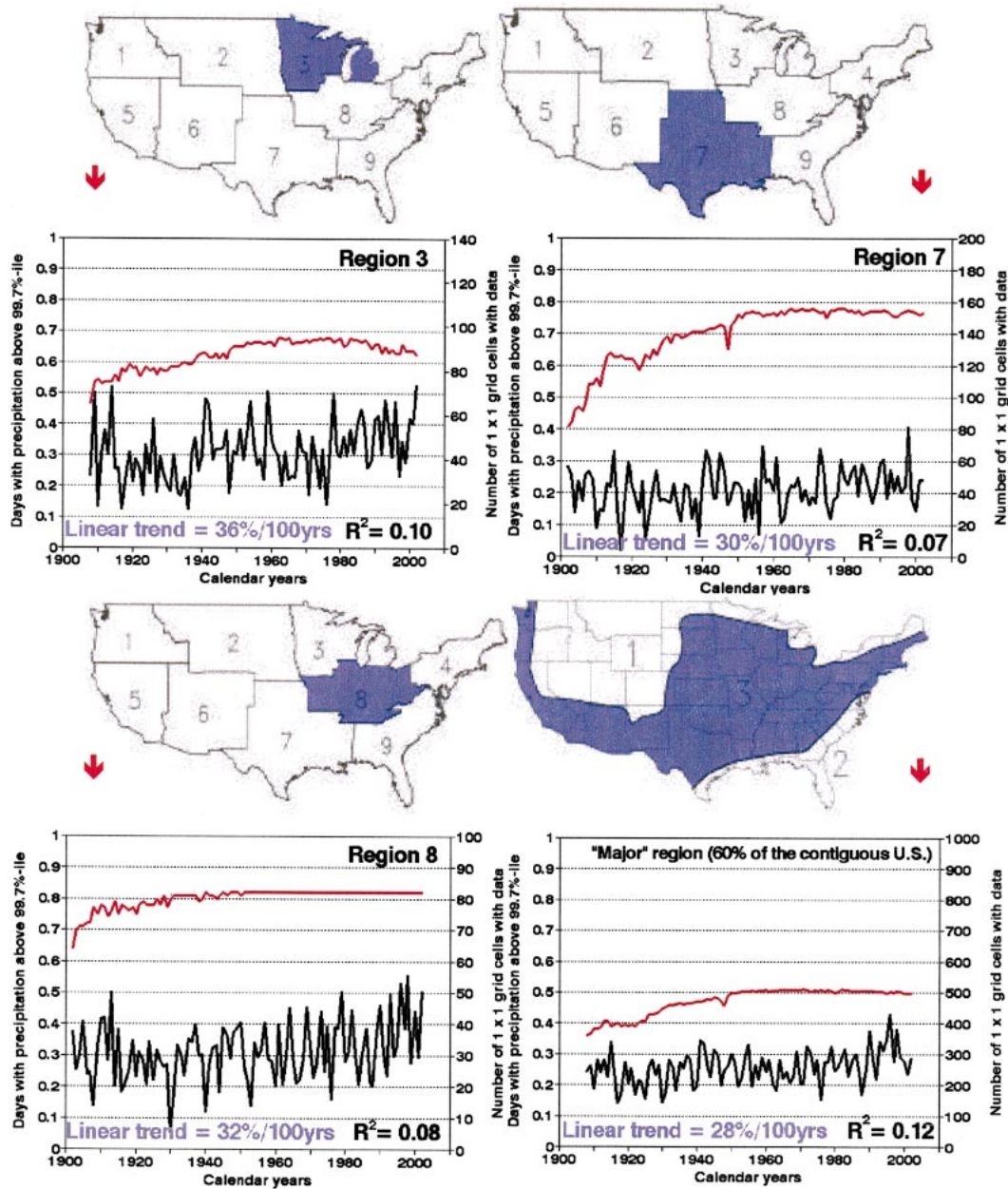


FIG. 9. Upper Mississippi, southern and midwestern United States, and the "major part" of the conterminous United States are the regions where significant trends in very heavy annual daily precipitation over the conterminous United States were documented for the 1908–2000 period (Groisman et al. 2002a,b). The updated (up to 2002) time series of frequency of very heavy precipitation (annual number of days with daily precipitation events in the upper 0.3%; black lines) and number of 1° x 1° grid cells with valid station data within these regions (red lines) are shown. Return periods of very heavy daily precipitation events (estimated for the 1961–90 reference period) vary from 2.9 yr for upper Mississippi and Midwestern United States to 4.3 yr for southern United States. All linear trend estimates for the 1908–2002 period shown in this graph are statistically significant at the 0.05 level or above; R^2 is the fraction of the time series variance described by the linear trend.

numbers for an updated period of 1908–2002 (bottom of Table 3A). There were two reasons for us to expect differences. We substantially updated the past period before 1948 and applied additional quality control procedures. Second, we have now added four dry years to

the end of the time series (1999–2002), which should have the effect of decreasing all trend estimates in precipitation. The numbers have changed, but all statistically significant results remain intact. Additional quality control procedures and significant data infusion for the

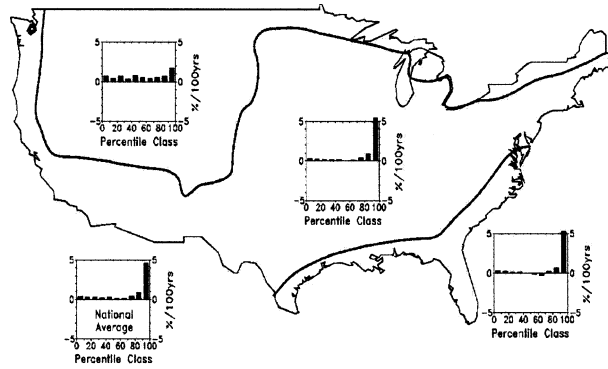


FIG. 10. Data are partitioned by three megaregions: one in which rainfall is strongly influenced by tropical cyclones, one in which more than 20% of precipitation falls in frozen form, and an intermediate region (Groisman et al. 2001c). For these regions and nationwide (shown in low left corner), the contribution of various parts of daily precipitation distribution to the linear trend of the total annual precipitation [% (100 yr)⁻¹] for the 1908–2002 period is shown. Trends are partitioned by 10th-percentile rainfall intensity classes. Linear trends for the upper 10% class in the intermediate region and nationwide are statistically significant at the 0.05 level. The intermediate region occupies 60% of the contiguous United States and is dubbed in Fig. 9 as the major part of the country.

pre-1948 period actually improved the nationwide trends making them statistically significant and also removed the old (and probably incorrect) negative estimate in the “snowy” region.

The increase of very heavy rainfall frequency in the southeastern coastal region is not statistically significant. We suspect that the high interannual variability in extreme precipitation events related to hurricanes over the southeast coastal region masks any trend in very heavy precipitation. Below, we investigate this aspect of very heavy precipitation trends in detail.

3) HURRICANE-RELATED PRECIPITATION

We identified all significant rainfall events above 50.8 mm that occurred in the zone of influence of each tropical cyclone or hurricane during the past century (Fig. 11) and assessed their influence over the southeast coast-

al region (Figs. 12 and 13; Table 4). Analysis of this stratified rainfall dataset clearly shows that there was no significant century-long change in hurricane-related precipitation along the coast. This is in spite of the fact that the total precipitation has increased (Table 4), and the frequency of very heavy precipitation (*unrelated* to tropical storms) has significantly increased (Fig. 13). The frequency of hurricanes and tropical storms largely drives the hurricane-related precipitation time series shown in Fig. 12 (Landsea et al. 1999). An interesting (and highly debatable) question of whether the hurricane landfall intensity *per storm* has changed during the past century was not considered in this analysis.

c. Streamflow

Total and base streamflow have increased during the past 60 yr (Hubbard et al. 1997; Fig. 14) when averaged nationwide. Most of this increase occurred in the eastern two-thirds of the contiguous United States (Table 5). In those parts of the world where snow accumulation is not significant factor in annual runoff, regional changes of heavy precipitation and high streamflow frequencies are in agreement. Such a situation is not apparent in the western third of the contiguous United States where a significant portion of high and very high streamflow is associated with snowmelt. However, in the eastern United States, variations in the frequencies of very high streamflow and very heavy precipitation are well correlated (Fig. 15). Building upon previous findings by Karl and Riebsame (1989), we have shown that relative changes in high streamflow over most of the contiguous United States (when presented in relative units) actually exceed more than twofold those in heavy precipitation (Groisman et al. 2001a,c). One of our updated results of this analysis is presented in Fig. 16. It shows that during the past four dry years the contribution of the upper percentile classes to annual precipitation remains high or (at least) above the average, while the similar contribution to annual streamflow sharply declined. This could be anticipated because of the accumulative char-

TABLE 3a. Trends of the annual number of days with very heavy precipitation (above 101.6 mm day⁻¹) during the twentieth century. (top) Results by Groisman et al. (2001c) for the 1910–2000 period and (bottom) results for the 1908–2002 period based on the present dataset. Trends are given in percent of the long-term mean values for the 1961–90 period; R^2 represents the variance (%) explained by the trend. Asterisks (**) indicate statistical significance at the 0.01 level.

Region (partition in Fig. 10)	Station no.	Mean (day yr ⁻¹)	Linear trend	
			% (100 yr) ⁻¹	R^2 (%)
Southeast coastal	335	0.537	19	3
>20% frozen precipitation	1322	0.023	-68	3
Intermediate	4169	0.148	45**	23
Southeast coastal	335	0.524	18	2
>20% frozen precipitation	1322	0.018	23	1
Intermediate	4169	0.147	32**	12
Nationwide	5181	0.129	28**	10

TABLE 3b. Trends of the annual amount of precipitation received in very heavy events (above $101.6 \text{ mm day}^{-1}$) during the 1908–2002 period. Trends are given in percent of the long-term mean values for the 1961–90 period; R^2 represents the variance (%) explained by the trend. Asterisks (**) indicate statistical significance at the 0.01 level.

Region (partition in Fig. 10)	Station no.	Mean annual precipitation from very heavy events (mm yr^{-1})	Linear trend	
			% (100 yr^{-1})	R^2 (%)
Southeast coastal	335	72	21	3
>20% frozen precipitation	1322	2	26	1
Intermediate	4169	19	34**	13
National	5181	17	30**	11

acter of high flow in large and medium rivers; it builds upon the base flow that remains low during dry years.

d. Snow cover and spring onset

A strong spring warming and thus an earlier spring onset (by 2–3 weeks during the past 50 yr) in the western United States has been documented in temperature, snow cover, and phenological records (Groisman et al. 2001a; Cayan et al. 2001; Easterling 2002; Figs. 5 and 17). Figure 17a provides an update of our previous estimates for March snow-cover changes during the 1950–2003 period (Groisman et al. 2001a). To construct these estimates we used daily in situ snow depth observations from the cooperative network up to March 2003. Trends in mean seasonal snow cover are shown in percent of the regional area. To better appreciate the relative significance of these changes, they should be compared with the seasonal climatology of snow-cover extent that varies from 6% in California and Nevada to 16% in valleys of the Northwest and 35% in the Missouri River basin. Figure 17b illustrates the similarity and unbiased nature of the in situ and satellite snow-cover extent estimates over the lower-elevation terrain of the country. In the West, the similarity of the interannual variations

of the in situ and satellite-based snow-cover extent estimates is preserved. However, there are systematic differences between them because the average elevation of the U.S. cooperative stations west of 105°W is approximately 300 m less than the average region elevation.

e. Evaporation

Evaporation is not directly measured by the U.S. standard meteorological network. Instead, measurements of evaporation from a pan filled with water are conducted in the warm season at a subset of stations. Brutsaert and Parlange (1998) suggested and Golubev et al. (2001) provided empirical evidence that over most of the contiguous United States, changes in “pan” and actual evaporation from the natural surface (e.g., grassland or bare soil) are inversely related to each other. This allowed us to interpret observed trends in the warm-season pan evaporation totals (May–September decrease over western two-thirds of the country) as an increase in actual evaporation (Lawrimore and Peterson 2000; Golubev et al. 2001).

f. Keetch–Byram Drought index

Each year, the United States suffers from natural and human-caused fires that can be especially devastating in the western, drier half of the country. Numerous indices have been developed to characterize the level of

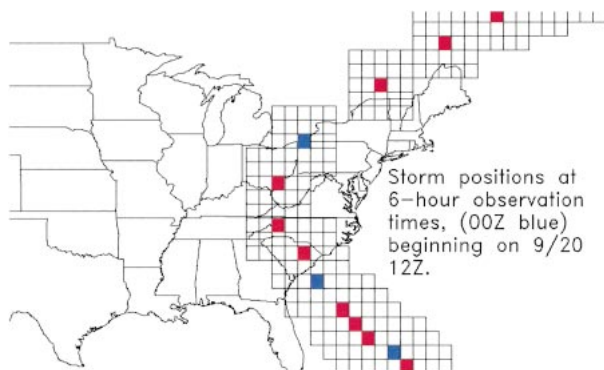


FIG. 11. An example of the data-gathering matrix as it follows Hurricane Hugo in 1989. We selected storm positions at 6-h observation times (colored $1^\circ \times 1^\circ$ boxes). Three boxes in each direction define the hurricane neighborhood. Each of the grid boxes records the heavy precipitation (i.e., that with a 24-hourly total above 2 in.) for 2 days before and after the storm-center passage. This precipitation is flagged as “hurricane related.”

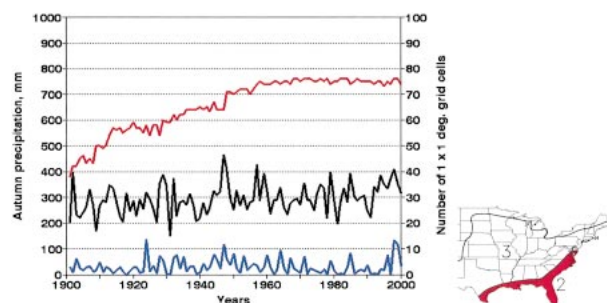


FIG. 12. Regional average autumn precipitation (mm) over the southeastern coastal megaregion shown in the map. Total (black line) and hurricane-related (blue line) precipitation as well as the number of $1^\circ \times 1^\circ$ grid cells with valid station data within this region (red line) are shown.

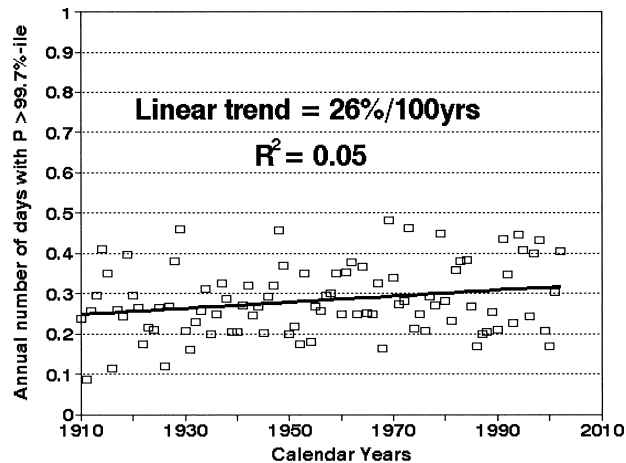


FIG. 13. Annual frequency of very heavy precipitation not related to tropical cyclones over southeastern coastal United States. Return period of the daily rain events with daily precipitation in the upper 0.3% unrelated to tropical cyclones is 3 yr. The area-averaged value of the 99.7th percentile for these events within the region is 110 mm; R^2 is the fraction of the time series variance described by the linear trend.

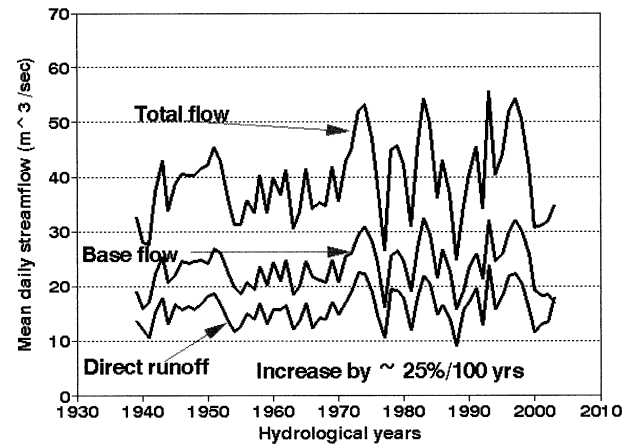


FIG. 14. Partition of annual runoff into base and overland flow (direct runoff) (update of Groisman et al. 2001b). Area averaging was performed only over the basins shown in Fig. 1d. Partition was performed using the routine developed by Rutledge (1998). All three time series exhibit similar positive trends of approximately 25% (100 yr)⁻¹ [or 15% (60 yr)⁻¹] that are statistically significant at the 0.05 level. Data for hydrological year 2003 are preliminary.

potential fire danger. Among these indices, the Keetch–Byram Drought index (KBDI; Keetch and Byram 1968) uses only daily temperature and precipitation information and estimates soil moisture deficiency on a scale ranging from 0 to 800 (0 is the point of no moisture deficiency and 800 is the most severe drought that is possible). The logic behind the index is that wet soil suppresses wild fires while dry soil organic matter enhances these fires and makes them difficult to control. High KBDI values are an indication that conditions are favorable for the occurrence and spread of wildfires. Various regional KBDI threshold values are used nationwide from Washington to Florida to characterize the severity of the drought conditions and/or the level of potential forest fire danger.

We calculated the KBDI for ~4150 stations having both daily temperature and precipitation data in the past century. The index was then area averaged over the nine regions depicted in Fig. 8. Figure 18a shows January, April, July, and October climatology of KBDI estimated for the 1961–90 reference period. No substantial systematic trends were found in the nationwide KBDI time series (Fig. 18b). This figure also shows the summer time series for the upper Mississippi and Midwest (re-

gions where a substantial improvement in mean summer wetness has occurred). In these regions, high values and a high interannual variability of summer KBDI in the first half of the century were followed by lower KBDI values and a lower variability since the mid-1950s. Figure 18c presents the frequency of the days with KBDI > 700 over the Southwest and >500 in the Northwest, Midwest, and Northeast. The summer soil moisture conditions (as ascribed by the KBDI) have improved in the upper Mississippi, Midwest, and Northwest, but the drought danger has increased in the Southwest, in California in the spring season (not shown), and, surprisingly, over the Northeast, despite the fact that annual precipitation here has increased. A century-long warming (Figs. 4 and 5) in this region is quite significant in summer, which reverses the tendencies of the precipitation contribution to soil wetness. Figure 18c is not completely conclusive for the Northeast region with days of KBDI above 500. This threshold is quite high (and thus infrequent for the region). However, the same conclusion (statistically significant at the 0.05 level or higher) emerges when the frequencies of the days with KBDI above 300 and 400 (not shown) were analyzed for this region.

TABLE 4. Southeast coastal region. Autumn precipitation characteristics. Asterisks (*) indicate statistically significant trends at the 0.05 or higher levels.

Precipitation type	Mean (mm)	Fraction of total	Trend, 1901–2000	
			%(100 yr) ⁻¹	R^2 (%)
Total	295	1.00	20*	9
Hurricane related	25	0.08	15	0
Other	270	0.92	21*	9

TABLE 5. Relative changes [%(100 yr)⁻¹] in the contiguous United States runoff during the 1939–2002 period. Statistical significance (at the 0.05 level) is marked by asterisks [Groisman et al. 2001b (updated)].

Region (partition in Fig. 10)	Total	Base	Direct
Contiguous United States	26*	25*	27*
Southeast coastal	4	–16	34
>20% frozen precipitation	9	6	17
Intermediate	35*	41*	28

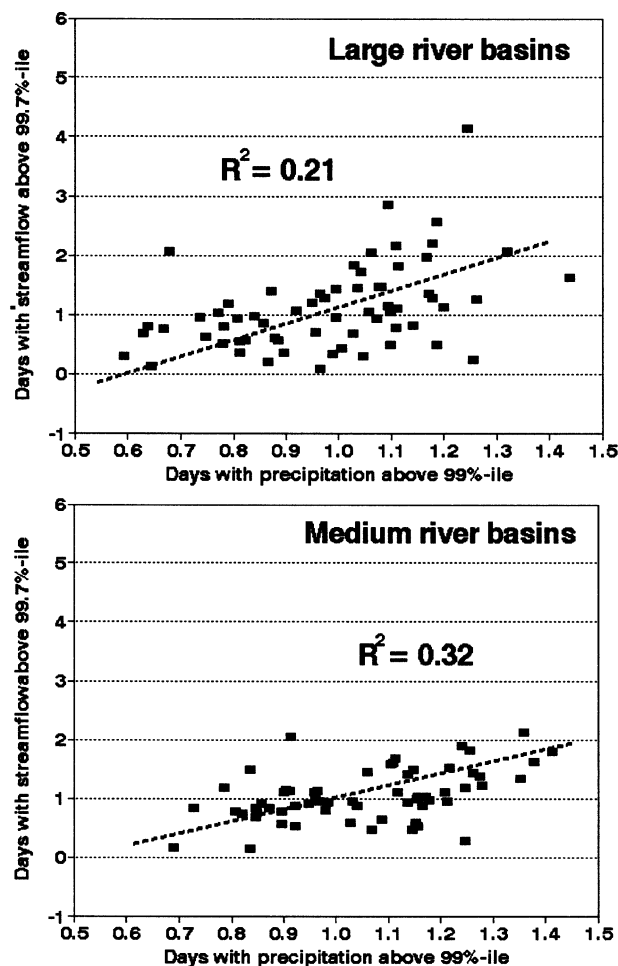


FIG. 15. Relationship between frequency of very high streamflow and very heavy precipitation in “medium” and “large” river basins with collocated rain gauges over the conterminous United States east of 95°W. Annual number of days with very heavy precipitation and very high streamflow are shown (upper 1% of precipitation events and upper 0.3% of streamflow events). The percentiles were selected to represent on average a threshold value exceeded about 1 day (yr)⁻¹ for both precipitation and streamflow. Medium river basins with areas between 260 and 2590 km² (100 and 1000 mi²) and large river basins with areas between 2590 and 25 900 km² (1000 and 10 000 mi²) were selected from Fig. 1d; R is the correlation coefficient.

g. Near-surface humidity

An increase in the near-surface temperature leads to an associated increase in the ability of the atmosphere to hold water vapor. Sun et al. (2000) have reported an increase of the near-surface specific humidity over the contiguous United States during the second half of the past century. In that study, they focused on conditions under clear skies in order to use an unambiguous, well-defined state of weather. They found that during the 1948–93 period, the mean annual near-surface specific humidity under clear skies had steadily increased with a mean rate of 7.4% (100 yr)⁻¹ (Fig. 19). With an increase in water vapor, one may expect an increasing potential for heavy precipitation with all types of weather

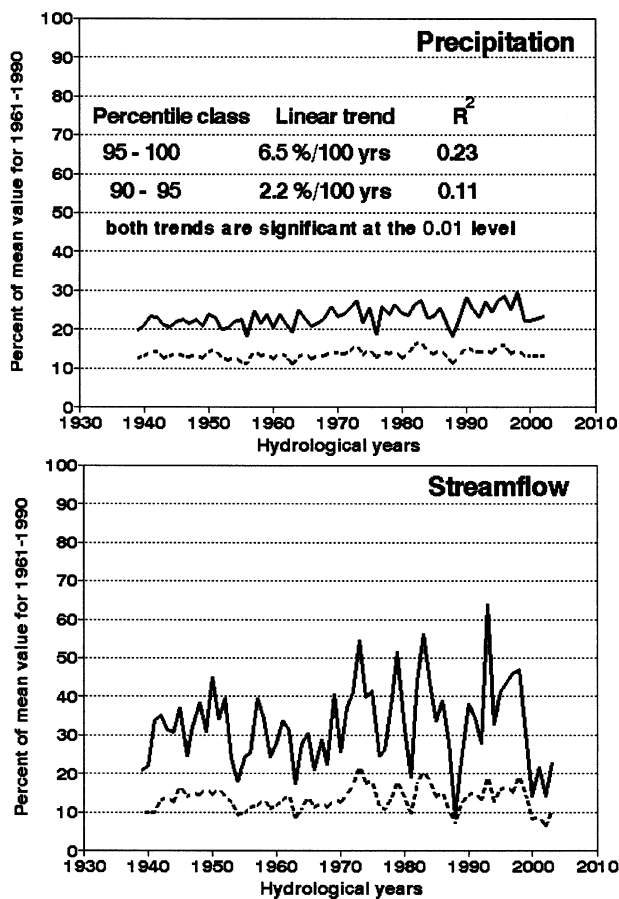


FIG. 16. Contribution of upper percentile classes of (top) daily precipitation and (bottom) streamflow to the total annual precipitation/streamflow over the gauged part of the contiguous United States (shown in Fig. 1d) during the 1939 to 2002–03 period [Groisman et al. 2001a,c (updated)]. Solid lines show contributions of the upper 95–100th percentile class and dashed lines of the 90–95th-percentile class, respectively. Streamflow data for hydrological year 2003 are preliminary; R^2 is the fraction of the time series variance described by linear trend.

er disturbances (e.g., airmass thunderstorms, tropical and extratropical storms, frontal precipitation, etc.).

h. Cloudiness

In the 1990s most of the cloudiness observations were discontinued or became incompatible with those in the past because of the implementation of an automated surface observation network. For a 40-yr-long period of homogeneous observations (from the early 1950s to the early 1990s), Sun et al. (2001) documented a significant increase in total, low, and cumulonimbus (Cb) cloudiness (Figs. 20–22). A nationwide increase in Cb is consistent with the increased frequency of heavy and very heavy precipitation (Fig. 23; Tables 2 and 6), while a nationwide increase in stratocumulus (Sc) is consistent

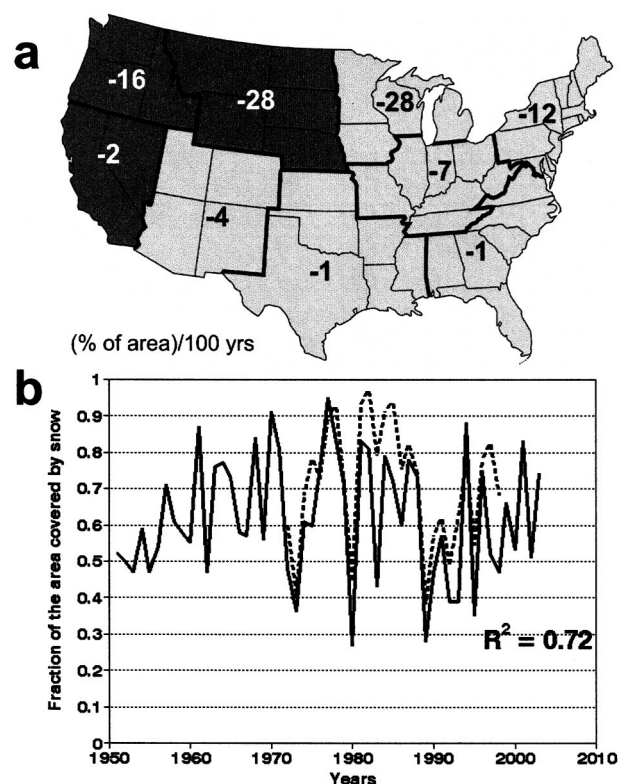


FIG. 17. (a) Trends [$\% (100 \text{ yr})^{-1}$] in the Mar snow-cover extent from the in situ data for the past 54 yr [1950–2003 period; Groisman et al. 2001a (updated)]. Regions with statistically significant trends at the 0.05 significance level are dark shaded. (b) Time series of in situ (solid lines) and satellite (dashed lines; visual imagery; Robinson et al. 1993) snow-cover extent observation for Jan over the north-eastern United States; R is the correlation coefficient.

with the increase of total precipitation.¹ The nonlinearity in summer Cb frequency changes (a large increase in the 1950s and steady thereafter) is not a spatially uniform phenomenon and may be related to droughts in the 1950s in the southern half of the country (e.g., in the same decade, the summer Cb frequency in the Midwest was above normal). However, the largest changes in the Cb frequency have occurred in the intermediate seasons, especially in spring. Therefore, in Figs. 22 and 23, the geographical pattern of the Cb and very heavy precipitation frequency changes in the spring season is shown. Figure 22 shows that all over the country, for trends statistically significant at the 0.05 level, positive trends outnumber negative trends almost sixfold (46 versus 8). The probability that this number of statistically significant positive trends occurred by chance from a total of 127 sites is miniscule. The probability of ob-

¹ Stratocumulus clouds themselves are not necessarily precipitation-producing clouds. However, because of a peculiarity of the U.S. cloud observing practice, Sc (and Cb) receive the highest priority in cloud-type reporting. As a result, annually about 50% of precipitation events from unobscured skies (i.e., when cloud type is still reported) occurred in the presence of Sc.

taining that number of statistically significant negative trends by chance is close to 0.5. The frequency of very heavy spring precipitation events² over the contiguous United States has increased during the past 50 yr. Nationwide and in two regions (Northeast and Southwest), linear trends of the frequency of these events are statistically significant at the 0.05 level (Fig. 23; Table 6).

i. Near-surface 10-m winds

It is very difficult to interpret the observed decrease [about $-5\% (50 \text{ yr})^{-1}$] during the second half of the twentieth century in nationwide near-surface wind speed recently reported by Groisman and Barker (2002; Fig. 24). The wind information used in this assessment was homogenized and quality controlled. The data processing (appendix A) was designed to avoid inhomogeneity in mean values. Although this has been achieved, two stepwise increases in the number of stations with available data (first in 1948 and then in the early 1970s) have noticeably reduced the variance of the regionally averaged time series for relatively rarely observed nationwide cases when hourly wind speed was recorded only for the hours when snowfall was reported. Changes in observation practices caused by automation in the 1990s strongly affected the frequencies of reports of calm weather and, to some extent, very strong winds (Groisman and Barker 2002). However, this is not likely the major cause of this monotonic decrease since the mid-1960s. While most wind observations were made at airports and/or coastal areas in unobstructed locations, we cannot definitely attribute this decrease to climate change or to the land-use change. Both causes can be argued though. Global warming (and warming over the United States; Figs. 3–5) can generate more frequent “summer type” weather conditions that in general are characterized by lower winds than in cold-season months. Conversely, construction and even tree growth in neighborhoods surrounding airports can change the large-scale surface roughness that gradually reduces wind speed at 10 m above the ground.

j. Shifts in seasonal cycle

Seasonal shifts were reported in surface air temperature across the United States (Vinnikov et al. 2002), in snow-cover extent, spring onset, streamflow peak in the West (Groisman et al. 2001a; Cayan et al. 2001), and in the precipitation peak in Virginia (Druckenbrod et al. 2003). Druckenbrod et al. (2003) report a significant shift of the summer precipitation peak (from June in the late eighteenth century to early August at present). Figure 25 shows a notable redistribution of seasonal precipitation during the twentieth century just south-

² Above upper 0.3th percentile of seasonal daily events, meaning that the return period for such events ranges from 9 to 18 yr depending upon the region.

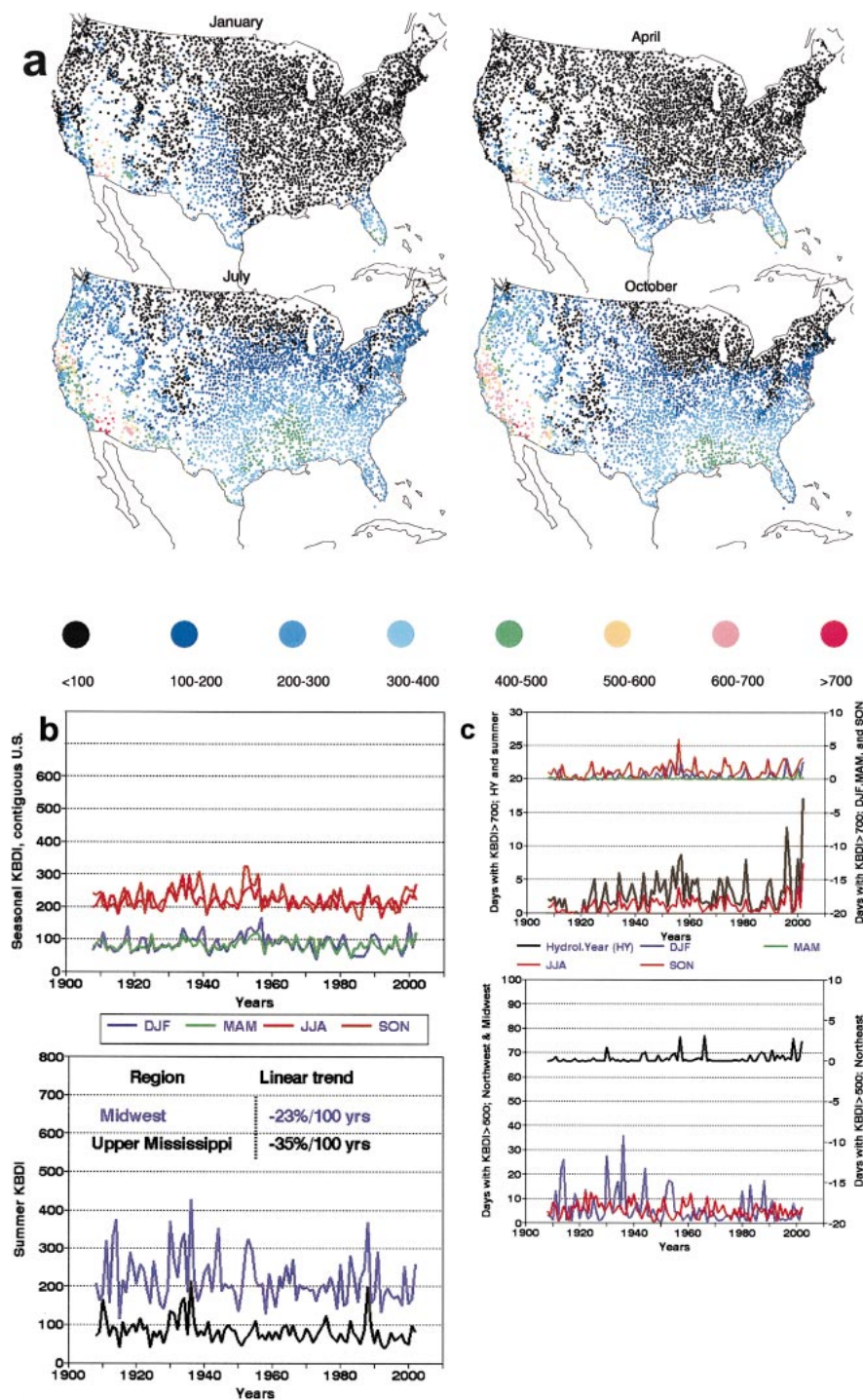


FIG. 18. (a) Seasonal climatologies of the KBDI over the contiguous United States. (b) Seasonal and summer KBDI time series (top) nationwide and (bottom) in the upper Mississippi and Midwest. (c) (Top) Annual and seasonal number of days with regional KBDI above 700 (highest drought danger) over the Southwest. Linear trends of all time series except Mar–Apr–May are statistically significant at the 0.05 level. (bottom) Number of summer days with regional KBDI above 500 (severe soil moisture deficiency) over three regions in the northern half of the United States (Northeast is black line, Northwest is blue line, and Midwest is red line). All linear trends are statistically significant at the 0.05 level.

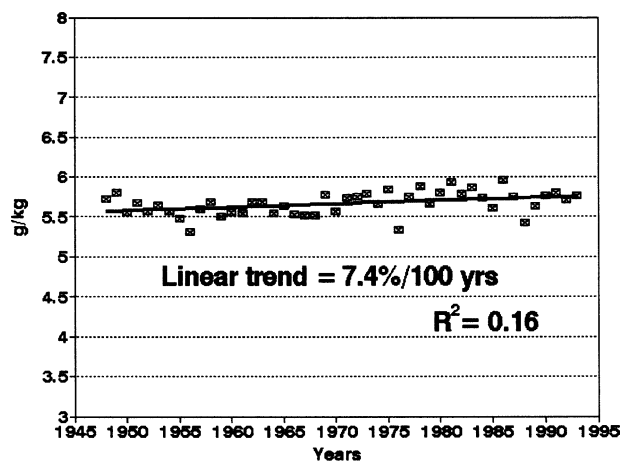


FIG. 19. Daytime annual clear-sky area-averaged specific humidity over the conterminous United States and its linear trend (Sun et al. 2000); R^2 is the fraction of the time series variance described by the linear trend.

ward of Virginia in the Carolinas. Daily data from more than 300 long-term stations were used to investigate trends in various precipitation characteristics in the Carolinas. A shift in the same direction was found at many locations. Significant interseasonal redistribution of precipitation during the past century is apparent. In this redistribution, a summer rainfall decrease by 17% (100 yr^{-1}) is compensated by an autumn increase by 25% (100 yr^{-1}). In the first third of the past century the average summer precipitation (400 mm) exceeded the mean autumn precipitation (235 mm) in the Carolinas by a factor of 1.7. However, in the last 30 yr the ratio between these two seasonal totals was about 1.25 (355 mm versus 280 mm for the long-term mean values). Comparison of long-term monthly precipitation for the past 20 yr and for the first 20 yr in the beginning of the

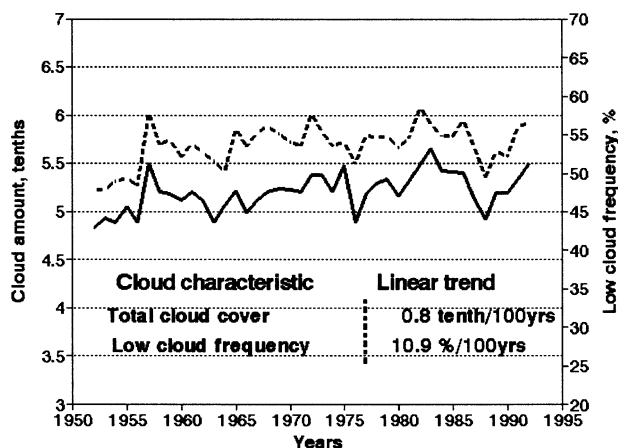


FIG. 20. Daytime annual frequency of area-averaged low-level cloudiness (solid line) and total cloud amount (dashed line) over the conterminous United States using the data of 127 serially complete first-order stations shown in Fig. 1b (Groisman et al. 2001c). Both trends are statistically significant at the 0.01 or higher levels.

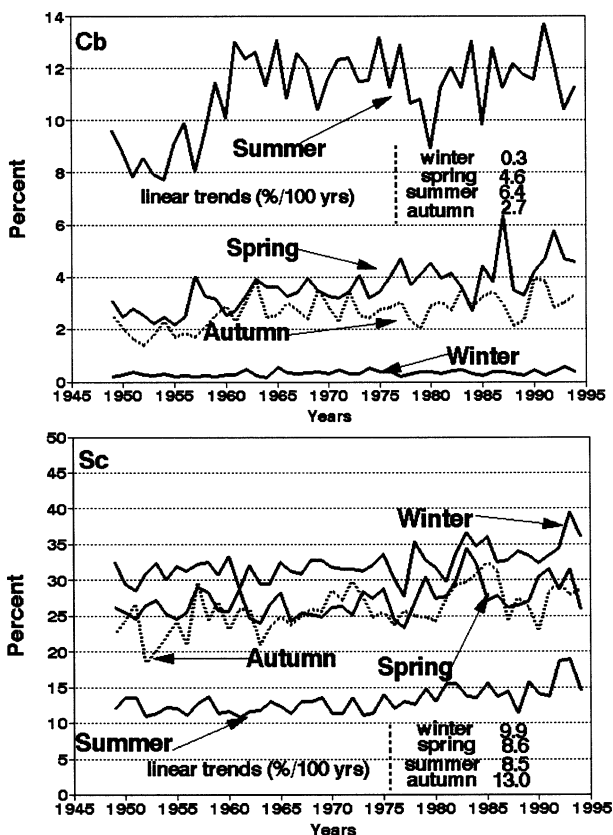


FIG. 21. Seasonal frequency of occurrence of daytime (top) Cb and (bottom) Sc when total cloud cover is above 0.2 (area averaged over the conterminous United States; Sun et al. 2001; Groisman et al. 2001c). All time series have statistically significant increasing trends at the 0.01 or higher levels.

century (not shown) reveals statistically significant differences at the 0.05 level or better for two autumn months (increase in September and November) and two summer months (decrease in June and July). In the 1900–19 period, the peak monthly precipitation oc-

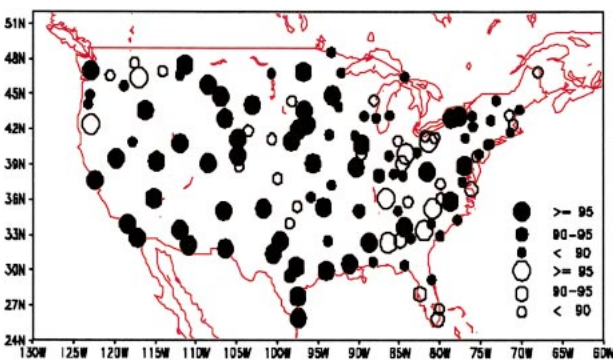


FIG. 22. Spatial distribution of the linear trend in spring cumulonimbus frequency over the period 1952–92. Black circles represent increasing and blank circles decreasing linear trends (Groisman et al. 2001c). Dot sizes are proportional to statistical significance of the trends.

curred in July. During the past 20 yr (1983–2002) this peak shifted to August. These changes, summer dryness and increased rainfall in autumn, were not related to changes in hurricane activity or to changes in the contribution of very heavy (4 in.) rainfall events to seasonal totals.

5. Summary and conclusions

In the previous section, we provided or cited observational evidence about the contemporary changes in various near-surface meteorological and hydrological variables over the conterminous United States. These are summarized in Table 7. Below we offer a view of their mutual consistency over the past 50 yr when the observation network is most comprehensive.

Warming, especially in the northern half of the conterminous United States (Figs. 4 and 5) is related to a reduction in spring snow-cover extent (Fig. 17a), an earlier snow retreat (Groisman et al. 2001a), and earlier onset of spring- and summerlike weather conditions (Cayan et al. 2001). This in turn results in an increase in the frequency of cumulonimbus clouds (Figs. 21 and 22), which relates to the general increase in thunderstorm activity over most of the contiguous United States (Changnon 2001) and in a nationwide increase in “very heavy” precipitation (Figs. 7–9 and 23). There are indications that increasing flood damage over the conterminous United States during the past decades is partially associated with this increase. Demographics and economic growth are also likely contributors to the increased flood damage (Pielke and Downton 2000). The Carolinas are the only region of the conterminous United States where a decrease in the thunderstorm activity during the past 50 yr was documented (Changnon 2001); the summer rainfall decreased in these two states (Fig. 25).

Spring warrants special attention in the Northern Hemisphere land areas. In this season, the global snow-cover feedback tends to enhance any external forcing (Groisman et al. 1994). For the conterminous United States, spring warming was among the strongest observed in both minimum and maximum temperatures, but its spatial distribution was very uneven. It was concentrated in the western and northern regions of the country (cf. Fig. 5) where seasonal snow cover is mostly confined. There has been a significant increase in spring Cb frequency over the entire country (Figs. 21 and 22) during the past 50 yr. Therefore, we paid special attention to very heavy precipitation occurring in spring during these decades (Fig. 23; Table 6). The nationwide increase in the frequency of very heavy precipitation events above the upper 0.3th percentile corroborates the changes in the Cb frequency. In spring most notably, we encountered a substantial shift in the return period of very rare events and, therefore, potentially damaging events (Table 6).

An asymmetric pattern of the diurnal temperature cy-

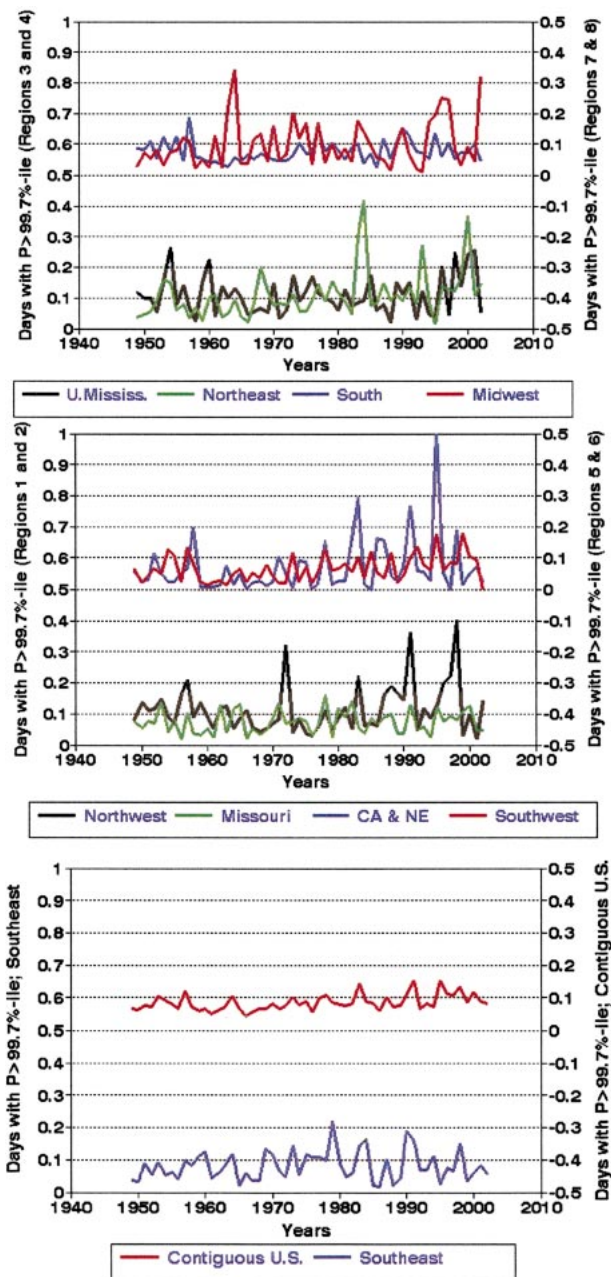


FIG. 23. Very heavy spring precipitation over the contiguous United States during the second half of the twentieth century. Area-averaged 99.7th percentiles used to define very heavy precipitation, and some statistical characteristics of these time series are provided in Table 6. Regions are those indicated in Fig. 8.

cle changes was first reported for the contiguous United States (Karl et al. 1991): minimum temperatures are increasing more than maximum temperatures. Durre et al. (2000) have shown that summer extreme maximum temperatures depend upon the antecedent soil moisture. In the case of a general intensification of the water cycle over the country (Fig. 6; Golubev et al. 2001) and some reduction in summer KBDI values (at least in the north

TABLE 6. Spring daily precipitation thresholds, P , for the 99.7th percentile precipitation events over the conterminous United States. Return period of these events is estimated for the 1961–90 reference period, RP, and according to linear trends of the frequency of these events in years 1949 (RP_1) and 2002 (RP_2). Linear trends in the frequency of these events for the past 54 yr (1949–2002; in percent of the mean frequency for the reference period) and respective changes in return periods between first and last year of this time interval. Bold font indicates regions where linear trends are statistically significant at the 0.05 or higher levels.

Subregion	P (mm)	Return period (RP, RP_1 , RP_2) (yr)	Linear trend of the event frequency			$RP_2 - RP_1$ (yr)
			[% (50 yr) ⁻¹]	R^2 (%)		
Northwest	35	10, 11, 7	48	3		−4
Missouri River basin	45	13, 15, 12	16	1		−2
Upper Mississippi	50	10, 10, 8	18	1		−2
Northeast	55	9, 17, 6	87	15		−11
California and Nevada	50	17, 31, 9	122	6		−22
Southwest	35	18, 22, 11	76	10		−11
South	95	14, 14, 12	10	0		−1
Midwest	75	10, 14, 8	48	4		−6
Southeast	100	12, 14, 11	18	1		−2
48-states average	60	13, 15, 10	42	18		−5

of the country, Midwest, Northwest, and upper Mississippi where decreasing trends in KBDI are significant), we can speculate that these may be a contributor to the pattern of the contemporary warming over the conterminous United States. That is, the observation that minimum temperatures have increased more than maximum temperatures in summer may be associated with the intensification of the water cycle.

In humid regions (the eastern United States), an increase in summer minimum temperature (Fig. 5) is related to an increase in the probability of severe convective weather (Dessens 1995) and is likely related to changes in the frequency of heavy and very heavy rain events. In Fig. 15, we have shown the relationship between high streamflow and heavy precipitation in the eastern two-thirds of the country. The onset of spring in the northwestern quadrant of the conterminous United States controls snowmelt streamflow that triggers the peak seasonal runoff. A lack of a noticeable increase in

winter precipitation, more frequent thaws associated with winter and spring warming, and a reduction in the seasonal length of stable snow cover act to smooth the peak runoff and shift it to earlier dates (Groisman et al. 2001a). Warming for some parts of the country (Southwest, Northeast) has led to summer dryness and an increase in potential fire danger (Fig. 18c).

Regarding trends for the entire century, we find a century-long increase in temperature and precipitation (including heavy precipitation). Much of the increase in heavy and very heavy precipitation has occurred during the past three decades. An increase in precipitation and streamflow over the eastern United States is in opposition to an increasing dryness in the Southwest. In the Southwest, Figs. 4–6 and 18c combined show that significant warming, and no appreciable changes or even a decrease in annual precipitation, lead to a year-round increase in the frequency of extremely high KBDI values.

What are the causes of all the observed trends? Unfortunately, data themselves and/or their analysis cannot provide answers to this question. These questions are better addressed by physical models of the global climate system. Their results are more credible when projections based on these models roughly correspond to conditions observed during the past century. Below, we cite three projections (in addition to obvious warming and observed intensification of the hydrological cycle over most of the country) that could be compared (tested) with the observed changes over the contiguous United States.

- Summer dryness in the centers of the continents as a result of the CO₂-induced global warming was first suggested by Manabe et al. (1981). There are some indications that during the past 50 yr this scenario (despite a total precipitation increase) holds up in dry regions of northern Eurasia (Groisman et al. 2003a,c) and over the southwestern quadrant of the conterminous United States (Fig. 18). However, over most of

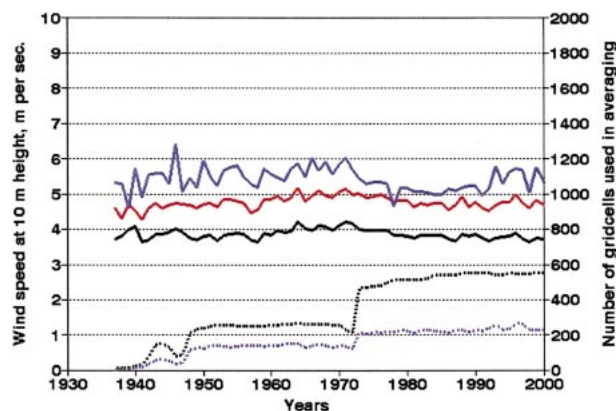


FIG. 24. Nationwide annual wind speed at 10 m above the ground averaged for all hours (black line) and separately for hours with liquid and frozen precipitation (red and blue lines, respectively). The number of $1^\circ \times 1^\circ$ grid cells used in the averaging routine are also shown [dotted lines; average (top line) and during snowfall events (bottom line)].

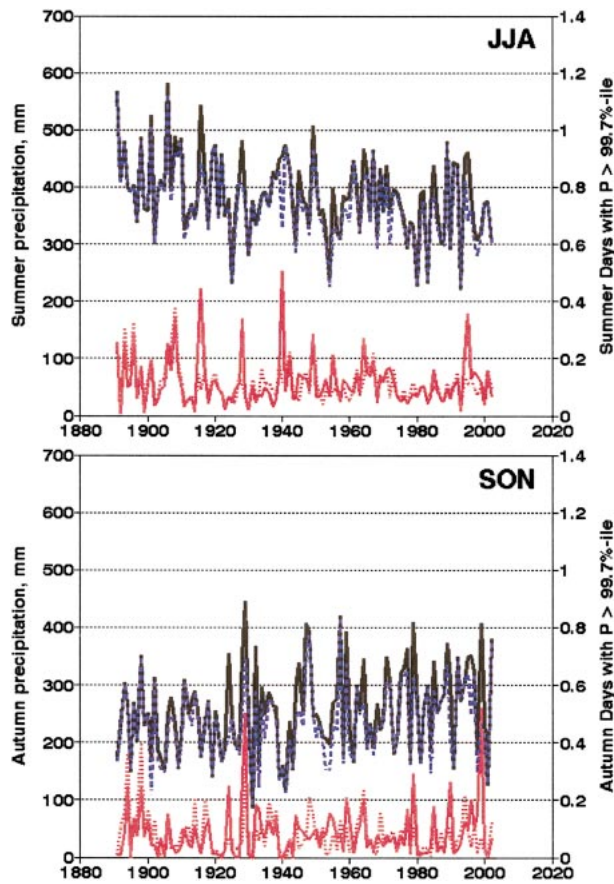


FIG. 25. Summer (Jun–Jul–Aug) and autumn (Sep–Oct–Nov) precipitation over the Carolinas. Seasonal precipitation (black and blue lines) and frequency of days with very heavy precipitation (daily rain events above the 99.7th percentile of ~ 100 mm with return period of approximately 10 yr; red lines). Daily precipitation is based on 353 long-term cooperative meteorological stations in the Carolinas and their 100-km neighborhood. Total (solid lines) and non-hurricane-related events (dashed lines) are presented.

the eastern United States (particularly over the Mississippi River basin) this is not evident. We can speculate that perhaps an insufficient longitudinal extent of the North American continent and its significant maritime exposure at the latitudes of the conterminous United States prevented the significant region of summer dryness from developing over most of the country during the past century. Another possibility is that this

projected feature of global warming does not hold up and/or that the scale of changes is insufficient for this feature to be detected for the conterminous United States.

- Enhancement of changes of any sign due to snow-cover feedback, which is especially prominent in the spring season, was suggested by Groisman et al. (1994). Throughout this paper, we demonstrated, using several variables (temperature, snow-cover extent, Cb, and very heavy precipitation), that during the past 50–100 yr changes in spring are substantial and are among the strongest over the conterminous United States.
- Most of global climate models project an increase in precipitation intensity with global warming (Houghton et al. 2001; Kharin and Zwiers 2002; Trenberth et al. 2003). In their assessment of rainfall intensity changes in the transient greenhouse gas simulation using a coupled atmosphere–ocean global circulation model (ECHAM4–OPYC3 for 1900–2099), Semenov and Bengtsson (2002; their Fig. 4) looked at results of the simulated changes of the contribution of the upper 10% quantile of daily precipitation to the annual total precipitation over the conterminous United States for the twentieth century. These were compared to the empirical results of Karl and Knight (1998). A close resemblance of positive trends, mean values, and the amplitude of the interdecadal variability suggests that the observed changes are in part related to an increase in greenhouse gases. The only other region of the United States that was assessed by Semenov and Bengtsson (2002) was the northeastern quarter of the country, which roughly corresponds to northeast and midwest regions of this study. Comparing observations in this region with changes in number of days with heavy precipitation (upper 10% of precipitation events) from this model, reveals a similar increase of approximately 10% over the twentieth century in both time series. The only discrepancy is that the model grid cells “drip” precipitation twice as frequently as “nature” in point observations.

A significant number of studies link variations of the hydrological cycle over the conterminous United States with major macrocirculation variables such as El Niño–Southern Oscillation, North Atlantic Oscillation, Arctic Oscillation, Pacific decadal oscillation, and with the de-

TABLE 7. Contemporary changes of the hydrological cycle over the conterminous United States, where \uparrow and \downarrow indicate increases and decreases, respectively.

Changes in the twentieth century		Changes in the past 50 yr	
Mean precipitation	\uparrow	all the left and	
Min temperature	\uparrow	Spring max temperature	\uparrow
Mean streamflow	\uparrow	Spring snow cover in the west	\downarrow
Heavy and very heavy rains in the east	\uparrow	Cloudiness (total, low, Cb)	\uparrow
High streamflow events in the east	\uparrow	Near-surface humidity	\uparrow
Wet conditions in the Mississippi River basin	\uparrow	Evaporation	\uparrow
Dry conditions in the Southwest	\uparrow	Near-surface wind speed	\downarrow

velopment of the North American monsoon system (Cayan et al. 1999; Gershunov and Barnett 1998; Mauget 2003; Wallace and Thompson 2002; Barlow et al. 1998; Higgins et al. 1997). While acknowledging these efforts, we want to point out that this study is mostly an attempt to log and summarize what we know about the long-term changes over the regions of the conterminous United States. Parameterization of these changes by assigning them to the above-mentioned macrocirculation variables was beyond the scope of our study.

When we define significant trends, we compare the trend estimate with its variability and claim that, despite this variability, the estimate is not equal to 0 with a given level of confidence. Variability of a trend estimate (especially for century-long time series) is much less than the variability of the time series itself, and the practical value of the statistical significance of the trend estimate can be questioned when compared to the variability of the time series. However, for a substantial part of the nationwide area-averaged variables described in this paper, the absolute values of trends for the period of observations are comparable to or even exceed standard deviations of the time series. This is true for annual temperature, precipitation, heavy and very heavy precipitation, specific humidity under clear skies, total cloud cover, frequency of very heavy precipitation, contribution of heavy and very heavy precipitation to annual totals, and seasonal frequency of the Cb and Sc cloudiness.

Acknowledgments. NASA Grant GWEC-0000-0052 and the NOAA Climate and Global Change Program (Climate Change and Detection Element) provided support for this study.

APPENDIX A

Area-Averaging Routines

Stations tend to cluster around major metropolitan areas and are sparse in mountainous terrain. Missing values are present in most of the records. Both of these factors had to be accounted for to properly represent the regional/national values of the various components of the hydrological cycle derived from in situ observations. Area-averaged calculations presented in this paper, except for the joint analyses of precipitation and streamflow, all use the same method. First, we selected the reference period with the most data availability to estimate the long-term mean values for each element for each season. For all elements but surface wind, the period selected was 1961–90. For surface wind this period was 1973–92. For each region, season, and element, we first estimated the anomalies from the long-term mean values at each station and then arithmetically averaged these anomalies within $1^\circ \times 1^\circ$ grid cells. Then these anomalies were regionally averaged with the weights proportional to their area (i.e., proportional to the cosine

of the median latitude of the grid cell). Data from the large regions use the regional area weights to form the national average. The long-term mean values (normals) were area averaged in a similar fashion and added at the final stage to the area-averaged anomalies. This approach emphasizes underrepresented parts of the country. It also allows the preservation of the regional time series unaffected by the changing availability of data with time. A detailed description of the preprocessing and special area-averaging routine used to compare regional streamflow and precipitation (Figs. 15 and 16) is provided in Groisman et al. (2001c). For precipitation, this procedure is exactly the same as that used by Karl and Knight (1998).

APPENDIX B

Methods of Trend Estimation

We tested the presence of systematic change in the time series using two standard methods: least squares regression (Draper and Smith 1966; Polyak 1996) and a nonparametric method based on Spearman rank order correlation (Kendall and Stuart 1967). We calculated the standard error of the linear trend estimate (or t statistic for rank order correlation) and assumed that the trend (increase/decrease) is statistically significant at the selected significance level (0.05 or higher) when the signal-to-error ratio (or the value of the t statistic) is above the threshold corresponding to the selected percentage points of a normal (Student) distribution for a two-tailed test.

When the less-powerful nonparametric test gave positive results regarding the statistical significance of a systematic monotonic trend, we accepted it. When the test based on linear regression showed a potentially significant trend, we detrended the time series and checked the autocorrelation function. We tried to fit it to one of two possible models: first-order autoregression model, $AR(1): X(t) = \alpha X(t-1) + \varepsilon(t)$ or the first-order moving average error model, $MA(1): X(t) = \varepsilon(t) - \alpha \varepsilon(t-1)$, where $\varepsilon(t)$ are independent random variables for different t and $|\alpha| < 1$ (Box and Jenkins 1970). Then we tested the assumption that $\alpha = 0$ (i.e., that the residual time series after the removal of the linear trend became independent with time). If α differed insignificantly from 0, we accepted the initial conclusion on the trend significance. When, at the 0.05 level of confidence, it appears that $\alpha \neq 0$ (in our analyses of these cases α was always positive), we estimated the linear trend error again to account for a reduced number of degrees of freedom than used initially for the linear trend error estimate. Then we reassessed the conclusion about the statistical significance based on linear regression. Among the results presented in this paper, autocorrelated residuals were sometimes found in the annual temperature, precipitation, and streamflow time series, especially when they were averaged nationwide. The resid-

uals of the frequencies of heavy and very heavy precipitation events and of seasonally averaged variables were never found to be autocorrelated except by random chance.

In our test of statistical significance of linear trends, we assumed that the area-averaged time series are normally distributed. Keeping in mind that hundreds of sites are typically used in the regional average, this assumption usually works even for a frequency of very rare events (such as very heavy and extreme precipitation). However, Fig. 18c gives an example when this assumption does not hold. To compare the summer results in the Northeast, Northwest, and Midwest, we used the same KBDI threshold of 500 for all. During the twentieth century, the summer season in the Northeast had extremely few days with KBDI > 500, and, thus, their frequency cannot be considered as normally distributed. To preserve the integrity of our estimation process, we selected lower KBDI thresholds for the Northeast and repeated trend analyses (section 4f).

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