**Contemporary Changes of the Hydrological Cycle over the Contiguous United States: Trends**

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## Abstract

Over the contiguous U.S. precipitation, temperature, streamflow, heavy and very heavy precipitation and high streamflow in the East have increased during the 20th century. In the past 50 years, in addition to these changes, increases in evaporation, near-surface humidity, total, low, and convective cloudiness, earlier snow cover retreat and spring onset in the West, and a decrease in near-surface wind speed have been documented.

## Introduction

This paper summarizes our knowledge about contemporary changes of the various components of the surface hydrological cycle over the contiguous U.S. derived mostly from in-situ observations. While the contiguous U.S. covers less than 4% of the globe, the world largest economy and one of the most productive agricultural regions reside in this area. During the past 100 years, the climate of the U.S. has been well recorded. This allows us to reproduce here a comprehensive picture of climatic changes for the 20th century that in many aspects is superior (has more details) to those for other parts of the world. While presenting this picture we caution the reader against extrapolation for the forecast of the future changes. Not all tendencies that have been quantified for the past century (past 50 years) will hold up. 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 (IPCC 2000, Chapter 2) and regional "surprises" are increasingly possible in the extremely complex, non-linear Earth climatic system. Below, we use primarily our publications and extensive NCDC data holdings to describe the changes in the hydrological cycle over the contiguous U.S. element by element with the major focus on very heavy precipitation events.

## Data used

The digital archive of the U.S. Cooperative network (NCDC 1998) contains about 18,000 stations comprised of daily records of precipitation, minimum and maximum temperatures, snowfall, snow depth, pan evaporation, and daily weather occurrence information. For study of the long-term changes of the hydrological cycle over the contiguous U.S., we selected ~6000 stations with sufficiently long records over the reference period of 1961-90 (Figure 2 in Groisman et al. 2001a). Reference periods are required in the area-averaging used to generalize our results within regions (cf., Groisman et al. 2001a,b) and are necessary due to the need to

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account for missing values in the long-term station records. Although the number of stations with available data is greatest during the past 50 years, a significant improvement in the data coverage for the pre-1948 period has been achieved in the past year through an ongoing effort to digitize early records (Groisman et al. 2002). This improves our ability to assess century-long changes in characteristics of the atmospheric hydrological cycle that have long return periods *and* a small spatial extent (in particular, frequencies of very heavy and extreme convective precipitation events). For conclusions about mean monthly and annual temperature, we used a subset of 1221 high quality long-term cooperative stations, U.S. Historical Climatology Network (USHCN, Easterling et al. 1996). Several important meteorological elements (humidity, cloudiness, atmospheric pressure, and wind speed) are not observed at cooperative network stations but are available only at synoptic stations. Most of the digital information from the approximately 250 major U.S. synoptic stations (cf., Figure 2 in Sun et al. 2001) starts around 1950. An additional suite of synoptic data is available since 1972. Here, we use a subset to assess the changes in 10-m winds (1268 stations with homogenized near-surface wind; Groisman and Barker 2002). Results for streamflow described in this paper are based on the same daily data set (Figure 1) that was used by Groisman et al. (2001a,b). This data set represents an update of long-term homogeneous river gage data used by Lins and Slack (1999) that, in turn, originated from the USGS Hydro-Climatic Data Network (Slack and Landwehr 1992).

**Figure 1.** River basins covered by the set of long-term streamflow gages (Lins and Slack 1999; 19.3% of the contiguous U.S.).

## Trends

***Temperature.*** Nationwide changes in temperature were not monotonic in the 20$^{th}$ century (http://lwf.ncdc.noaa.gov/oa/climate/research/2001/ann/us-summary.html). The warming during the first and last thirds of the century was interrupted by a cooling period in the middle of the century. Geographically, the most significant century-long increase in surface air temperatures occurred in the northern and western parts of the country with some decrease in the southeast (Figure 2). Ten years ago, Karl et al. (1991) found significant asymmetry in warming over the U.S. as well as over other parts of the extra-tropics: minimum temperature increased more rapidly than maximum temperature and in many cases much or even all of the warming trend was attributed to the nighttime warming. Over the contiguous U.S., a substantial increase in minimum temperatures has been documented mostly in the cold season (winter and spring) with the biggest changes confined to the northwestern quadrant of the country and to the past 50 years (Figures 2 and 3). During the past 50 years, summer minimum temperatures have increased nationwide except Texas and Oklahoma (Figure 3).

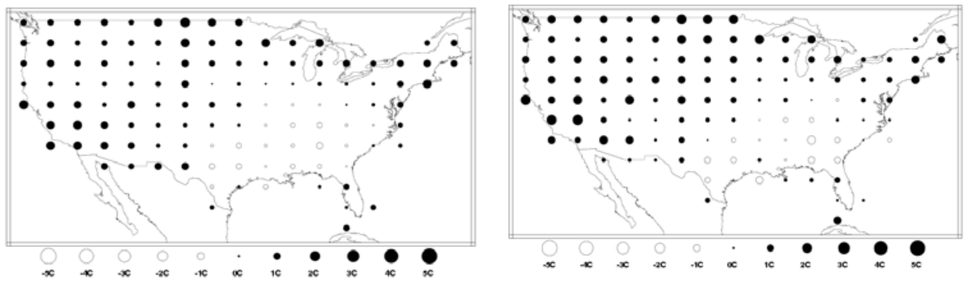


**Figure 2.** Annual mean (left) and minimum (right) temperature trends for the past century (1900-2000). Individual trends from USHCN stations have been area-averaged within a 2.5º x 3.5º grid. Dark dots indicate increasing and open dots decreasing trends. The dot sizes are proportional to the trend values (in ºC/100 years) with the largest sizes equal to ±5ºC/100 years.

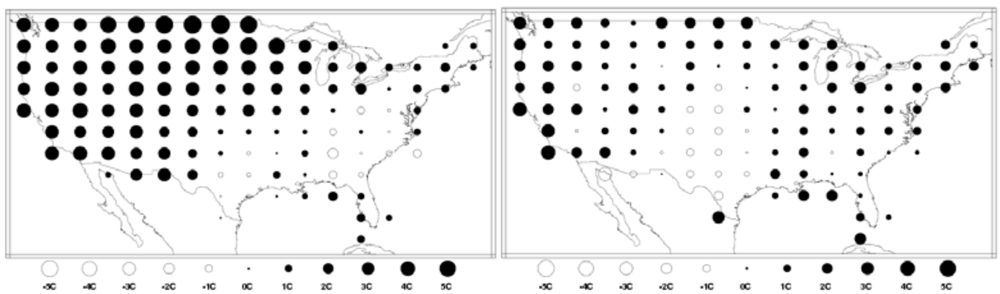


**Figure 3.** Spring (left) and summer (right) minimum temperature trends for the past 51 years (1950-2000) based on the USHCN. Dark dots indicate increasing and open dots decreasing trends. The dot sizes are proportional to the trend values (in ºC/100 years).

***Precipitation.*** The precipitation record is characterized by much more spatial and temporal variability than temperature. Consequently, trends constitute a small fraction of this variability and precipitation anomalies in each wet or dry year usually are much greater than any trend at each location. However, changes in precipitation tend to accumulate, thus affecting the surface water balance (soil moisture, runoff, and level of the lakes), and it is important to know how these trends are manifested in terms of intra-annual distribution and intensity. It has been suggested that with an increase or decrease of total precipitation, disproportionate changes occur on the upper end of its distribution (Karl and Knight 1998; Groisman et al. 1999; Easterling et al. 2000). Therefore in this section, we present estimates of changes in ***mean*** and ***very heavy***

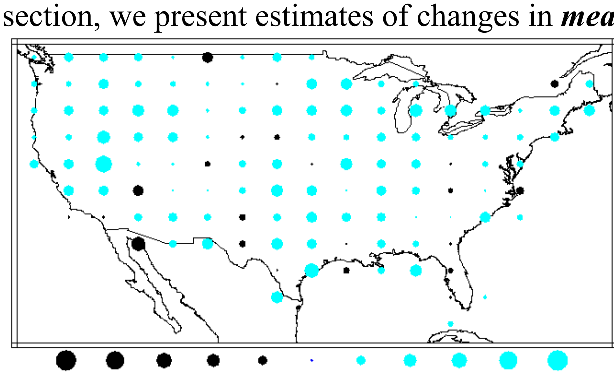


**Figure 4.** (update and reformatted from Groisman et al. 2001a). Linear trends (%/100yrs) of annual precipitation (1900-2000). Individual trends from USHCN sites have been area-averaged within a 2.5º x 3.5º grid. Light dots indicate increasing and black dots decreasing trends.

precipitation separately. Nationwide time series of ***mean precipitation*** indicate significant interannual variability with two particularly noteworthy dry decades (1930s and 1950s), and followed by the relatively wet past three decades implying a century-long precipitation increase (http://lwf.ncdc.noaa.gov/oa/climate/research/2001/ann/us-summary.html). Geographically, the increase varies by magnitude and is absent over parts of the southeastern and southwestern U.S. (Figure 4). The nationwide increase of 7 to 15%/100 years in seasonal precipitation is confined to spring, summer, and autumn (Karl and Knight 1998; Groisman et al. 2001a). An analysis of

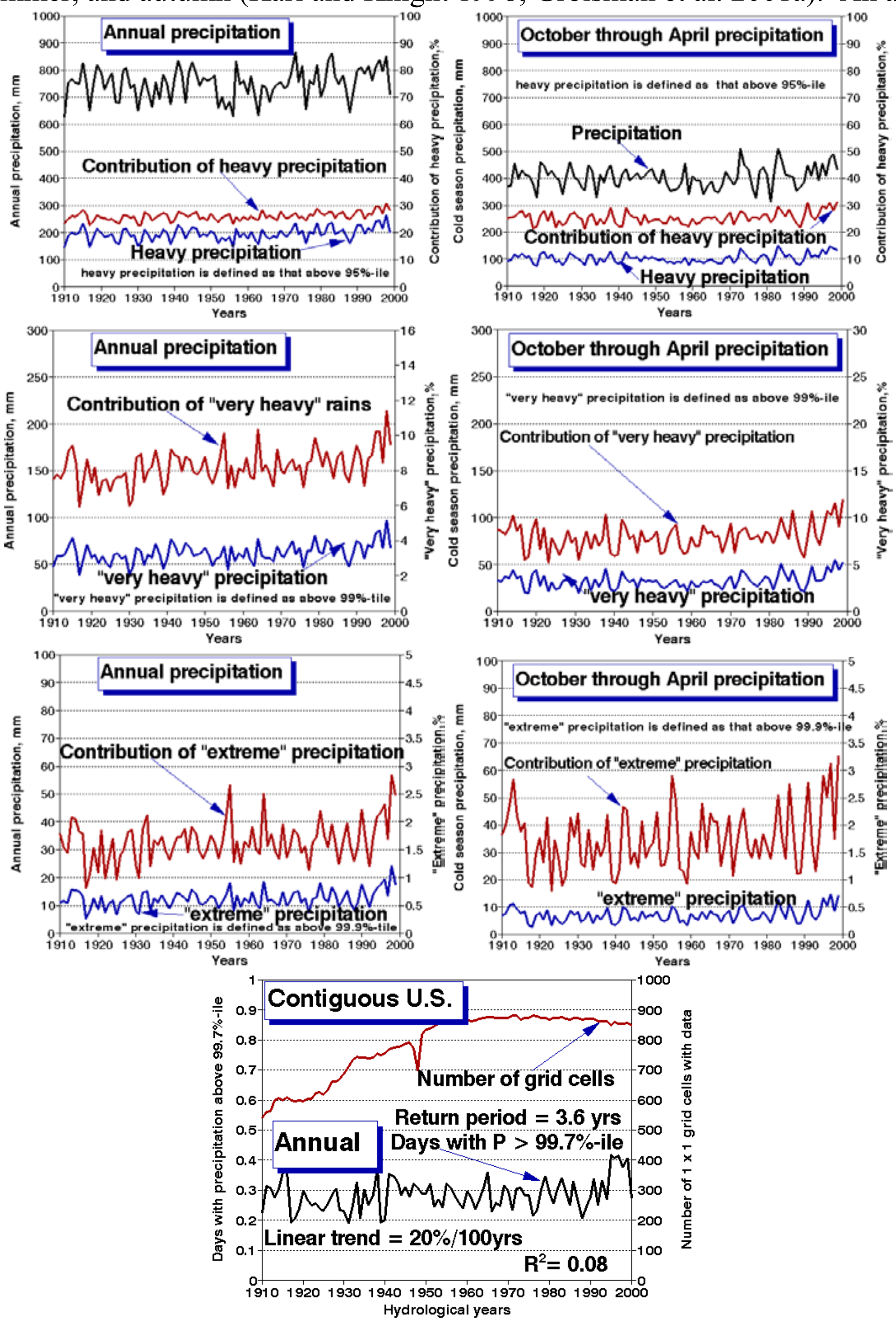


**Figure 5.** Changes in "heavy", "very heavy", and "extreme" precipitation over the contiguous U.S. (from archive of Groisman et al. 2001a,b; 2002).

**Table 1.** Annual daily precipitation thresholds, P, for 99.7%-ile precipitation events. Return period for such events varies from 3 to 5 years depending upon the frequency of days with measurable precipitation.

| Region number in Figure 6 | Sub-region | P, mm |
|---|---|---|
| 1 | Northwest | 45 |
| 2 | Missouri River Basin | 50 |
| 3 | Upper Mississippi | 65 |
| 4 | Northeast | 65 |
| 5 | California & Nevada | 65 |
| 6 | Southwest | 45 |
| 7 | South | 105 |
| 8 | Midwest | 80 |
| 9 | Southeast | 105 |
| | ***48-states average*** | ***70*** |

***heavy and very heavy precipitation*** requires the use of the densest possible network and an assessment of the longest time scale available in order to make meaningful statements about changes in frequency of these rare events. Some kind of regional averaging is required to suppress small-scale variability that is due to the occurrence of convective storms. In our first analyses, we sometimes used absolute units as thresholds to characterize "heavy" and "very heavy" daily precipitation events (e.g., 2 inches or 100 mm). Below we present results based on the frequency of occurrence of the rain event in each location and define as "very heavy" an

**Table 2**. Trend characteristics (1910-1999 years) of the time series in Figure 5

| Characteristic | Mean value | Linear trend and its variance %/100yrs | $R^2$ , % |
|---|---|---|---|
| Annual precipitation | | | |
| Total | 750 mm | 6 | 5 |
| "Heavy", 95%-ile | 200 mm | 16 | 12 |
| "Very heavy", 99%-ile | 65 mm | 24 | 15 |
| "Extreme", 99.9%-ile | 13 mm | 33 | 11 |
| Contribution to annual totals | | | |
| | Absolute | Relative change | |
| "Heavy" | 26% | 2.7 | 20 |
| "Very heavy" | 8% | 1.5 | 17 |
| "Extreme" | 2% | 0.4 | 9 |
| Cold season (October through April) | | | |
| Total | 400 mm | 6 | 2 |
| "Heavy", 95%-ile | 100 mm | 16 | 6 |
| "Very heavy", 99%-ile | 32 mm | 25 | 7 |
| "Extreme", 99.9%-ile | 7 mm | 36 | 7 |
| Contribution to cold season totals | | | |
| | Absolute | Relative change | |
| "Heavy" | 25% | 2.5 | 8 |
| "Very heavy" | 8% | 1.5 | 7 |
| "Extreme" | 2% | 0.5 | 5 |

event that is observed in one of 100 (above the 99%-ile) or not more than in 3 in one thousand daily rain events (i.e., above the 99.7%-ile at each location). This approach allows "more even" spatial coverage across the diverse areas of the country concerning infrequent (and thus 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 U.S. for the 99.7%-ile of annual 24-hour rain event (i.e., "very heavy" precipitation event). Figure 5 shows changes in nationwide (contiguous U.S.) annual and cold season precipitation with additional partition of daily rainfall into "heavy" (above the 95%-ile)," very heavy" (above the 99% and 99.7%-les), and "extreme" (above the 99.9%-ile) events. Table 2 provides some statistical characteristics of the time series shown in this figure. These pictures and table indicate that, while mean precipitation increase was barely visible during the past century (and was statistically insignificant in the cold season), heavy and very heavy precipitation increased markedly as did the proportion of their totals attributed to these events. Regionally and seasonally, changes in "very heavy" precipitation vary significantly, and are most notable in the eastern two-thirds of the country and primarily in the warm season when the most intense rainfall occurs (Figure 6).

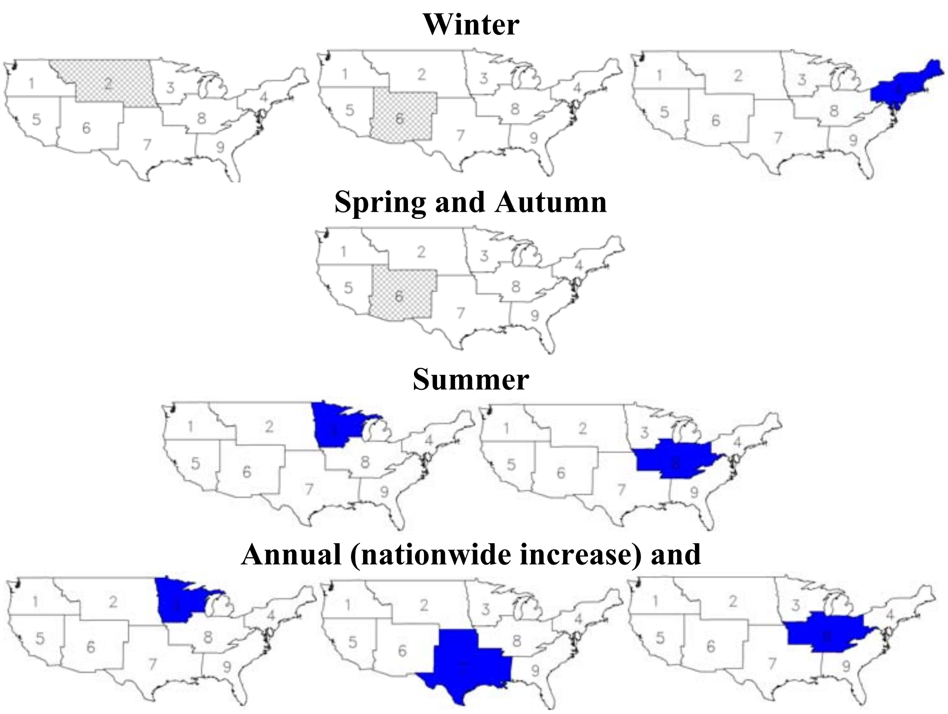


**Figure 6.** Areas of significant trends in "very heavy" daily precipitation (99.7%-iles) over the contiguous U.S. (1908-2000). Dark blue areas indicate increasing and hatched areas decreasing trends. Only trends that are statistically significant at the 5% level are shown. For seasonal precipitation, 99.7%-ile threshold usually indicates daily rain events with return period above 10 years while for annual precipitation it is in the range of 3 to 5 years.

In an attempt to evaluate the effects of "very heavy" precipitation on streamflow, we singled out a region where more that 80% of annual totals fall in liquid form (eastern and southern portions of the country or 67% of the contiguous U.S) and additionally outlined within it a southeast coastal region with a significant contribution of hurricane-related rainfall to annual totals (Figure 7, (Groisman et al. 2001b). In all these three mega-regions there was a general century-long increase in total precipitation and “heavy” precipitation but the increase in “very heavy” events was statistically significant only over the major part of the contiguous United States (central, eastern, and southern regions). We suspected that high variability in extreme precipitation events related to hurricanes over the southeast coastal region is masking trends in very heavy precipitation. Therefore, we identified all significant rainfall events (above 50.8 mm) that occurred in the zone of influence of each hurricane track during the past century and assessed them separately over this region. Analysis of this stratified rainfall data set clearly shows that there was no noticeable century-long change in hurricane-related precipitation along the coast, while total precipitation has increased and the frequency of “very heavy” precipitation *unrelated* to tropical storms has significantly increased (Figure 8, Table 3)

**Figure 7.** Partition of the contiguous United States into three regions. We singled out the regions where rainfall is strongly influenced by tropical cyclones and where more than 20% of precipitation falls in frozen form.

**Table 3.** Southeast coastal region. Autumn precipitation characteristics.

| Precipitation type | Mean mm | Fraction of total | Trend, 1901-2000 %/100yr | $R^2$ |
|---|---|---|---|---|
| Total | 295 | 1.00 | 20 | 9 |
| “Hurricane-related” | 25 | 0.08 | 15 | 0 |
| Other | 270 | 0.92 | 21 | 9 |

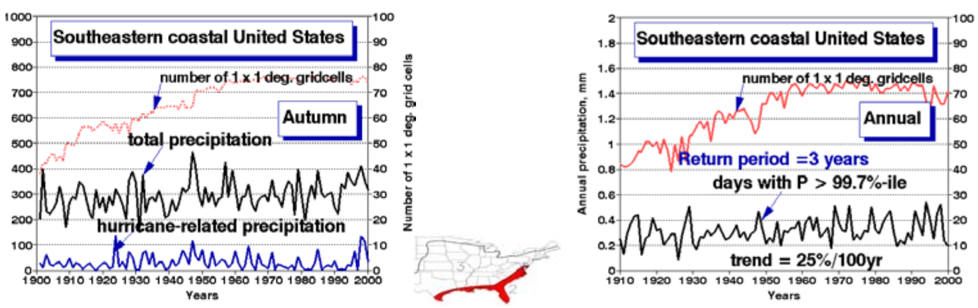


**Figure 8.** Southeast coastal region. ***Left.*** Autumn precipitation, mm. ***Right.*** Frequency of “very heavy” precipitation *not* related to tropical storms.

***Streamflow.*** When averaged nationwide, total and base streamflow has increased during the past sixty years (Hubbard et al. 1997; Figure 9). Most of this increase occurred in the eastern two-thirds of the contiguous U.S. (Table 4). Groisman et al. (2001a,b) investigated if one can imply from century-long trends of “very heavy” precipitation a similar or even a more prominent increase in “very high” streamflow. It appears from this analysis that this is not possible for the western third of the country where a significant portion of high and very high streamflow is associated with snowmelt. But in the eastern U.S., variations of the frequencies of “very high” streamflow and “very heavy” precipitation are well correlated. Building upon previous findings by Karl and Riebsame (1989), Groisman et al. (2001a,b) have shown that trends in high streamflow over most of the contiguous U.S (when presented in relative units) actually exceed more than twofold those in heavy precipitation.

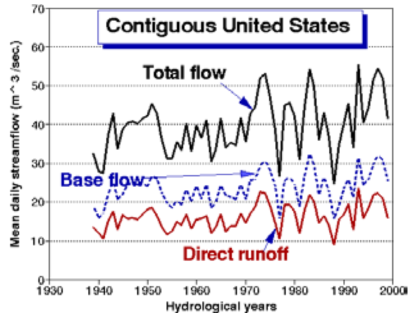


**Figure 9.** Partition of annual runoff into base and overland flow (direct runoff). Area-averaging was performed within the basins shown in Figure 1.

**Table 4.** Relative changes (%/10 years) in the contiguous United States runoff during the 1939-1999 period. Statistically significant (at the 0.01 level) linear trends are marked with asterisks.

| Region (partition in Figure 7) | Total | Base | Direct |
|---|---|---|---|
| "With snowfall" | 2.0 | 1.7 | 2.6 |
| Main part of the contiguous U.S. | 5.1* | 5.5* | 5.5* |
| Southeast coastal | 3.4 | 2.4 | 6.6* |
| Contiguous U.S. | 4.1* | 4.0* | 4.3* |

***Snow cover and spring onset.*** An earlier spring onset (by two to three weeks during the past 50 years) in the western United States was documented in temperature, snow cover, and phenological records (Figure 3; Groisman et al. 2001a; Cayan et al. 2001; Easterling 2002).

***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 U.S., changes in "pan" and actual evaporation actually mirror each other: increase in one means a decrease in the other and vice versa. This allowed us to interpret observed trends in pan evaporation (May-Sept. decrease over western two-thirds of the country) as an increase in actual evaporation (Lawrimore and Peterson 2000; Golubev et al. 2001). The increase in the warm season should be considered as a conservative estimate of total evaporation changes because in spring a further increase in evaporation should be expected due to an earlier spring onset.

***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 even under the clear-sky conditions (Sun et al. 2000). When these conditions turn to those preferential to precipitation, one may expect an increasing potential for heavy precipitation.

***Cloudiness*** observations are conducted only at synoptic stations and in the 1990s most of these observations were discontinued or became incomparable with those in the past due to the implementation of an automated surface observation network. For a 40-year-long period of homogeneous observations (from early 1950s to early 1990s), Sun et al (2001) documented a significant increase in total, low, and convective cloudiness. A nationwide increase in convective cloudiness and especially of *Cumulonimbus* had a direct impact on the frequency of heavy and very heavy precipitation (Figure 10; Sun et al. 2001; Groisman et al. 2001b).

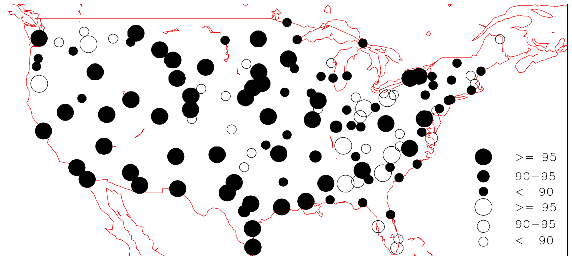


**Figure 10.** Spatial distribution of linear trend in Spring *Cumulonimbus* frequency over the period 1952-1992. Black circles represent upward and blank circles downward linear trends (Groisman et al. 2001b). Dot sizes are proportional to statistical significance of the trends.

***Near-surface 10-m winds.*** It is very difficult to interpret an observed decrease in nationwide near-surface wind speed recently reported by Groisman and Barker (2002). While most wind observations were made at airports and/or at the coast in unobstructed locations, we cannot definitely attribute this decrease to climate change or to the land use change. Both causes can be argued. Global warming (and warming over the USA) 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 reduce wind speed at 10 meters above the ground. Due to the uncertainties attributable to these two factors (and probably others), we can only report and bound the composite effect in observations to about -5%/50 years.

## Concluding remarks

In the previous section, we provided or cited observational evidence about the contemporary changes in various near-surface meteorological and hydrological variables over the contiguous U.S. They are summarized in Table 5. Warming (Figures 2 and 3) is related to an earlier snow retreat (Groisman et al. 2001a) and earlier onset of spring- and summer-like weather conditions. This in turn results in an increase in the frequency of convective clouds (Figure 10; Sun et al. 2001; Groisman et al. 2001b) and in a general increase in thunderstorm activity (Changnon 2001). An increase in summer minimum temperature (Figure 3) is related to an increase in the probability of severe convective weather (Dessens 1995) and thus in the frequency of heavy and very heavy rain events. We have already described the relationship between high streamflow

**Table 5.** Contemporary changes of the hydrological cycle over the contiguous United States. ↑ and ↓ mean increase and decrease respectively.

| Changes in the 20th century: | | Changes in the past 50 years all the left and | |
|---|---|---|---|
| Mean precipitation | ↑ | Evaporation | ↑ |
| Min. temperature | ↑ | Spring snow cover in the West | ↓ |
| Mean streamflow | ↑ | Near-surface humidity | ↑ |
| Heavy & very heavy rains in the East | ↑ | Cloudiness (total, low, convective) | ↑ |
| High streamflow events in the East | ↑ | Near-surface wind speed | ↓ |

and heavy precipitation in the eastern two-thirds of the country. In the West, the spring onset controls snowmelt streamflow that peaks the seasonal runoff cycle in this area. 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 tend to smooth this peak and shift it to earlier dates (Groisman et al. 2001a).

Of course, the most important questions would be "What causes all these changes?" and "Can we forecast that they will continue in the future?" Unfortunately, data themselves and /or their analysis can not provide answers to these questions. The most that we can do is link the observed changes to the changes in intermediate large-scale factors. Among them are general warming over the country, reduction of the meridional temperature gradient with global warming, changes in macro-circulation characteristics such as North Pacific Decadal Oscillation, annular variations in zonal circulation, El Niño/La Niña effects, or changes in the North American monsoon properties. To proceed further would be speculation. Therefore, these questions are better addressed by physical models of the Global Climatic System.

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