

Trends in precipitation and streamflow in the eastern U.S.: Paradox or perception?

David Small

Cincinnati Earth System Science Program, Department of Civil and Environmental Engineering, University of Cincinnati, Cincinnati, Ohio, USA

Shafiqul Islam and Richard M. Vogel

Department of Civil and Environmental Engineering, Tufts University, Medford, Massachusetts, USA

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[1] Many studies have reported that total precipitation is increasing across the United States with most of the increase resulting from a positive trend in the upper tail of the daily precipitation distribution. Other studies have found that low and moderate, but not high flows are also increasing across much of the United States. How can precipitation, especially that produced by intense events, increase without a corresponding increase in high flows? We analyzed trends in annual 7-day low, average and high flows along with seasonal precipitation that is averaged over individual basins. Our findings suggest that statistically significant trends in both fall precipitation and 7-day low flow are found in a large percentage of the basins in the upper Mississippi and Great Lakes regions of the country. A large fraction of the trends in annual precipitation can be explained by an increase in fall precipitation. By estimating trends in precipitation at the spatial scale of individual basins, we offer a simple explanation for the apparent paradox of lack of trends in high flows. At the spatial scale of individual basins, precipitation is increasing during the fall but not during the spring, the season when high flows are generally observed. The increase in fall precipitation appears to result in an increase in the low flows while the lack of trends in precipitation in spring explains the lack of widespread trends in the high flows. **Citation:** Small, D., S. Islam, and R. M. Vogel (2006), Trends in precipitation and streamflow in the eastern U.S.: Paradox or perception?, *Geophys. Res. Lett.*, **33**, L03403, doi:10.1029/2005GL024995.

1. Introduction

[2] There is growing evidence that total precipitation has increased across the United States over the last several decades [Karl and Knight, 1998; Groisman *et al.*, 2001; Kunkel *et al.*, 2002]. For example, Karl and Knight [1998] reported a 10% increase in annual precipitation across the nation that can be primarily attributed to large increases in precipitation during spring and fall with 53% of the increase in total precipitation coming from an increase in the upper ten percent of daily precipitation totals.

[3] A number of recent studies have also identified some trends in streamflows in the U.S. Lins and Slack [1999] analyzed records from relatively undisturbed watersheds across the U.S. and found that low to moderate (but not

high) streamflows have increased in some regions. Douglas *et al.* [2000] found that trends observed in annual maximum streamflows disappear after accounting for their spatial correlation. Groisman *et al.* [2001] found that streamflow has increased across the eastern United States during the month of maximum flow (spring for most stations) and that these trends can be attributed to increases in the intensity of extreme precipitation events during that season. Their results appear to contradict the findings of Lins and Slack [1999] and Douglas *et al.* [2000], but the main difference may be methodological rather than substantive [Lins and Cohn, 2003].

[4] The observed upward trends in extreme precipitation and the associated lack of trends in high streamflows have led some to suggest the existence of a paradox [Pielke and Downton, 1999]. Why do we observe that total rainfall and extreme rainfall over the United States is increasing while high streamflows are not? One possible explanation for this apparent paradox is that streamflow sensitivity to precipitation appears to be lowest for the high flows [Lins and Cohn, 2003], suggesting that high flows are much less likely to exhibit precipitation induced trends than either low or mean flows. Another possible hypothesis, which is addressed here, is that trends in precipitation during the season of the high flows are significant when averaged over large areas, but not when averaged over the small spatial scales of individual basins. Still another hypothesis considered here is that trends in precipitation may occur during the fall, a season when high flows do not typically occur.

[5] Most studies of trends in precipitation have averaged precipitation data over areas much larger than individual basins. We hypothesize that a simultaneous analysis of seasonal precipitation and streamflow data at the scale of individual watersheds is necessary to attribute trends in streamflow to trends in precipitation.

[6] This study addresses the following questions: Can the trends in low flow across the eastern United States be directly attributed to an increase in fall precipitation? Is the absence of observed trends in high flows due to a lack of trend in spring precipitation at the basin scale? Are trends in the annual average flow due to an increase in fall precipitation?

2. Data

[7] We selected the daily and annual streamflow data from the USGS Hydroclimatic Data Network (HCDN) [Slack *et al.*, 1993]. This data set of river discharges was developed for climate sensitivity studies and includes watersheds that

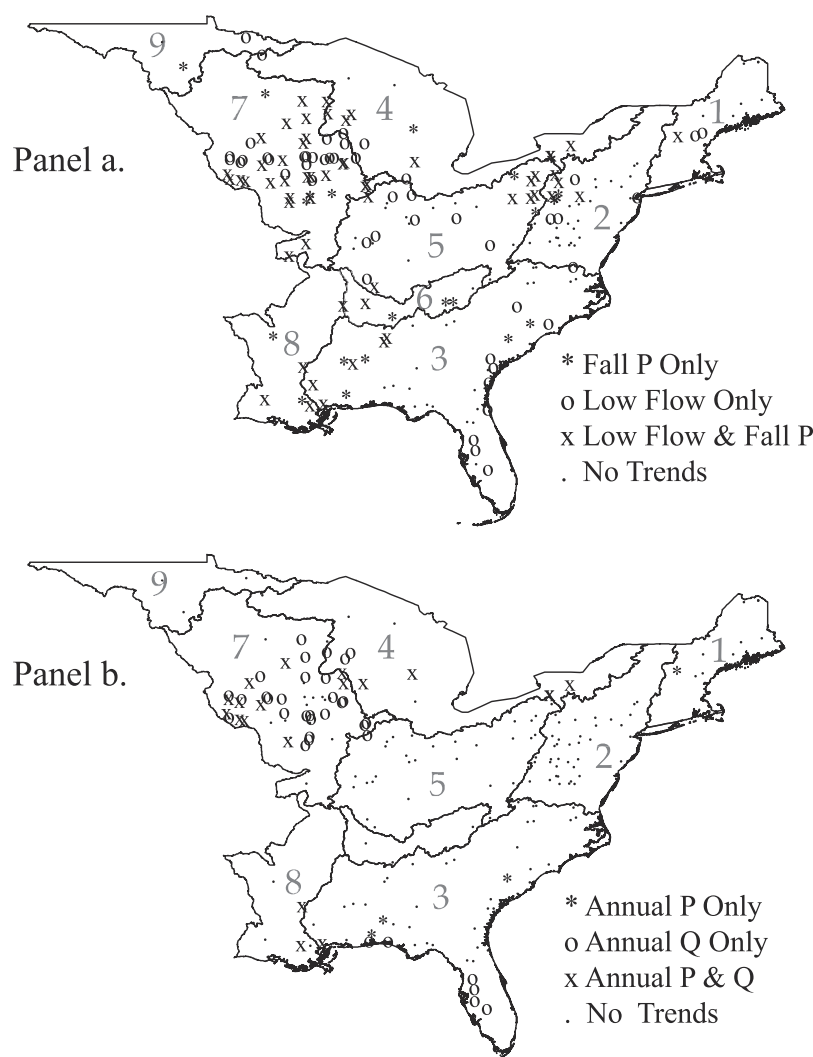


Figure 1. The locations of the stations used to identify trends in precipitation and streamflow in the nine water resources regions in the eastern half of the United States. (a) The location of streamflow stations in basins where trends were found in low flow and fall precipitation. (b) The same for annual average streamflow and annual precipitation.

were chosen because they have experienced minimal water withdrawals and/or water transfers. We consider 218 HCDN basins in the eastern U.S. with complete records over the period 1948–1997, with drainage areas greater than 100 square miles and with annual minimum 7-day low flows that were always greater than zero (Figure 1). The HCDN streamflow records are only complete over the period 1948–1988; hence they were augmented over the period 1989 to 1997, from USGS records, to produce 50 year sequences.

[8] The seasonal and annual precipitation time-series data are taken from the monthly PRISM data set available on a 4 km by 4 km grid [Daly *et al.*, 2000]. The PRISM climate modeling system has been used widely over the past decade as evidenced by over 390 citations to the original paper by Daly *et al.* [1994]. We use the PRISM data set in part because the fine spacing of the grid allowed us to average the monthly precipitation totals over each watershed.

3. Methods and Results

[9] We averaged the seasonal (DJF, MAM, JJA, SON) and annual total precipitation over the drainage area of each

of the 218 HCDN basins for each year over the period 1948–1997. Only those gridpoints from the PRISM precipitation data that are completely contained within the drainage area of each HCDN basin were included to estimate the average. From the basin-average precipitation, we calculated trends in the seasonal and annual precipitation totals for each basin and then estimated the statistical significance of the trend using a non-parametric Kendall tau test. We then estimated the annual minimum 7-day low-flow, the annual high flow and the annual average daily flow in each basin and estimated the magnitude and significance of trends associated with those variables using a significance level of $p < 0.05$.

[10] The results of the simultaneous analysis of trends in both precipitation and streamflow are summarized in Table 1. The elements on the diagonal in the table are the number of basins with significant trends in the individual streamflow and precipitation quantities. Off-diagonal elements are the number of the basins with significant trends in every possible combination of discharge and precipitation. Table 1 illustrates that the only combinations of both flow and precipitation variables with statistically signifi-

Table 1. The Number of the 218 Study Basins With Statistically Significant Trends in Streamflow and Precipitation^a

	Streamflow			Precipitation				
	Low	Annual	Flood	Winter	Spring	Summer	Fall	Annual
<i>Streamflow</i>								
Low	104	46	14 ^b	3 ^b	2 ^b	7 ^b	56	18
Annual	46	53	8 ^b	2 ^b	0 ^b	3 ^b	33	19 ^b
Flood	14 ^b	8 ^b	30	0 ^b	1 ^b	1 ^b	9 ^b	2 ^b
<i>Precipitation</i>								
Winter	3 ^b	2	0 ^b	9 ^b	1 ^b	0 ^b	1 ^b	2
Spring	2 ^b	0 ^b	1 ^b	1 ^b	4 ^b	0 ^b	1 ^b	0 ^b
Summer	7 ^b	3 ^b	1 ^b	0 ^b	0 ^b	10 ^b	7 ^b	4 ^b
Fall	56	33	9	1 ^b	1 ^b	7 ^b	78	15 ^b
Annual	18 ^b	19 ^b	2 ^b	2 ^b	0 ^b	4 ^b	15 ^b	53

^aThe numbers on the diagonal are trends in individual variables while off-diagonal elements are the number of basins with trends in both the column and row variable.

^bAny entry with less than 22 (10%) of the basins highlights seasonal and flow conditions associated with changes in precipitation and streamflow at a small percentage of the basins.

cant trends in a large number (more than 10%) of basins are for fall precipitation and the annual minimum 7-day low flow. Statistically significant trends in low flows were observed at 104 of the 218 stations, in fall precipitation at 78 stations and in both fall precipitation and low flow at 56 stations (all positive trends). We also found statistically significant trends in the average annual flow at 53 stations and in the high flows at 30 stations, but few of the observed trends in seasonal or annual precipitation in those basins were also statistically significant.

[11] Figure 1 shows the spatial distribution of stations with statistically significant trends in fall (annual) precipitation and low (annual average) flow across the eastern half of the country. The density of stations with statistically significant trends is highest in the upper Mississippi (water resources region 7) and Great Lakes (region 4). In both regions, we find statistically significant trends in both low flow and fall precipitation in over half of the basins. We find statistically significant trends in both low flow and fall precipitation at 29 of 54 basins in the upper Mississippi and at 6 of 13 basins in the Great Lakes region. Statistically significant trends in the annual average flow are also concentrated in the upper Mississippi (36 of the 54 stations) and Great Lakes (8 of 13 stations) regions.

[12] The largest trends in the low flow and fall precipitation were also found in the upper Mississippi (region 7) and Great Lakes (region 4) regions (not shown), consistent with the findings of Douglas *et al.* [2000]. The only statistically significant decreases in the low flow were found at 8 stations in the South Atlantic-Gulf region (region 3), consistent with Lins and Slack [1999]. All of the observed statistically significant trends in the fall precipitation are positive with magnitudes that are generally smaller than the trends in the low flows. The magnitudes of the statistically significant trends in the annual average flow are much smaller than the trends in the low flows and are largest in the upper Mississippi (region 7). The trends in the annual precipitation were also smaller than the trends in the annual average flow, consistent with previous findings that suggest an increase in annual precipitation tends to produce an amplified increase in annual streamflow in the U.S. [e.g.,

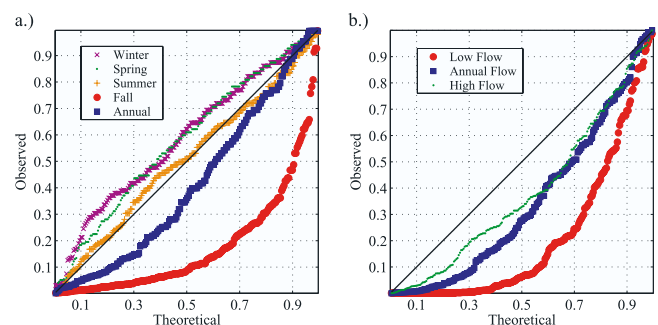
Sankarasubramanian *et al.*, 2001; Niemann and Eltahir, 2005].

[13] Rather than estimating a single value of field significance for each set of hypothesis tests, we present quantile-quantile (q-q) plots of the estimated p-values of the test statistics to enable us to evaluate if the significance levels follow a uniform distribution. Departures from the uniform distribution indicate one of two possibilities: (1) the null hypothesis of no trend must be rejected or (2) the hypothesis tests are not independent of each other because the flow and precipitation sequences exhibit spatial correlation.

[14] Figure 2 illustrates that the q-q plots of annual and fall precipitation both deviate from linearity (i.e., a uniform distribution), but the departure is clearly much larger for fall precipitation. A similar result is observed for streamflow, where the largest departure from the uniform distribution is observed in the low flows. The plots of annual average and high flows also deviate from linearity, but the largest deviation from linearity is observed in the low flows. The q-q plots for winter, spring and summer precipitation totals are all nearly linear (with a slope very near one). We conclude from the q-q plots that we must reject the null hypothesis of no trend for both low flow and fall precipitation series but not for high flow or spring precipitation.

[15] Rather than adjusting the trend tests to account for spatial correlation, we performed principal components (PC) analysis on the streamflow and precipitation records. Before performing the PC analysis, we divided the precipitation and streamflow time-series by the area of the basin and standardized by the mean and standard deviation to make them zero mean and unit variance. We estimated the empirical orthogonal functions (EOFs) and PC's for seasonal and annual precipitation and low, annual and high flow.

[16] The leading principal components of the fall precipitation (27.4% of the variance) and low flow (25.7% of the variance) capture the trend in each set of time series. The corresponding empirical orthogonal functions of fall precipitation and low flow (not shown) are very similar, indicating that the regional patterns of the trends in the low flow and fall precipitation share a common spatial correlation structure. This similarity suggests that the trends in low flow are due to trends in fall precipitation. The same is true for the annual precipitation and streamflow for which the leading EOFs also capture the trends in annual precipitation and are very similar to one another.

**Figure 2.** Quantile-quantile plots for the trend tests of (a) precipitation and (b) streamflow across the eastern United States.

[17] We analyzed trends in the leading PCs of fall precipitation and streamflow and found that they are both statistically significant and that the trend in the low flow is approximately 13% larger than the trend in fall precipitation. The magnitude of the trend in annual streamflow is approximately 41% larger than the trend in annual precipitation, similar to findings from previous studies that have suggested that trends in streamflow are amplified when compared to the trends in precipitation [e.g., Sankarasubramanian *et al.*, 2001; Niemann and Eltahir, submitted manuscript, 2005]. We observed no large or statistically significant trends in the leading PCs of high flow, winter, spring or summer precipitation. The only combination of precipitation and streamflow for which trends are large and statistically significant is low flow and fall precipitation.

[18] We have identified statistically significant trends in fall (annual) precipitation and annual minimum 7-day low (annual) streamflow across the eastern U.S. If we estimate the total increase in precipitation over 50 years for each season (in mm) and divide by the total increase in annual precipitation, we arrive at the percentage of the trend in total precipitation at each basin due to increases during the fall. We estimate that, on average, fall precipitation is responsible for 50.0 percent of the increase in annual precipitation in the 23 basins where we found statistically significant trends in annual precipitation. Over the 53 basins where we found statistically significant increases in annual average streamflow but not annual precipitation, fall precipitation contributed 61.3 percent of increases in annual precipitation. The majority of the increase in annual precipitation appears to be coming from an increase in fall precipitation.

[19] The process of creating gridded precipitation data can introduce spurious trends due to the relative sparseness of stations and the high degree of spatial smoothing. To validate the suitability of the PRISM data set for estimating trends we estimated trends in fall precipitation at 528 stations in the USHCN data set and compared them with trends estimated from the gridpoint in the PRISM data set nearest to each station. We also performed principal components analysis on both sets of data. A direct, point-by-point comparison of trend tests for fall (not shown) suggests that the statistically significant trends in the PRISM data set have the same sign as the statistically significant trends in the USHCN station data. The principal components analysis demonstrated that the EOF and PC of the trend component estimated from the PRISM gridpoints and the USHCN stations are nearly identical suggesting that while there may be differences at individual points, the large-scale patterns of the trends are very similar. This analysis appears to validate the use of the PRISM gridded data employed here for identifying trends in individual basins.

4. Conclusions

[20] We have simultaneously analyzed trends in streamflow and precipitation at 218 basins across the eastern half of the United States. We have found that the annual mean and low flow have increased during the period 1948 to

1997 across the eastern United States whereas the annual high flow has not. The observed trends in low flow, especially in the upper Mississippi and Great Lakes, can be explained by an increase in fall precipitation in a large fraction of the basins. We find that precipitation has not increased at the basin scale during the other seasons and suggest that this explains why the high flows have not increased. Trends in the annual average flow and the annual precipitation were also found at a number of stations, though the changes were not nearly as widespread as those in the low flows. In summary, fall precipitation and low flows have simultaneously increased across the eastern United States while spring precipitation and high flows do not show a widespread trend. Trends in annual precipitation and streamflow appear to arise primarily from the increase in fall precipitation.

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S. Islam and R. M. Vogel, Department of Civil and Environmental Engineering, Tufts University, 113 Anderson Hall, 200 College Ave., Medford, MA 02155, USA. (shafiqul.islam@tufts.edu)

D. Small, Cincinnati Earth System Science Program, Department of Civil and Environmental Engineering, University of Cincinnati, 765 Baldwin Hall, Mail Stop 210071, Cincinnati, OH 45221–0071, USA.