A step increase in streamflow in the conterminous United States

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[1] Annual minimum, median, and maximum daily streamflow for 400 sites in the conterminous United States (U.S.), measured during 1941–1999, were examined to identify the temporal and spatial character of changes in streamflow statistics. Results indicate a noticeable increase in annual minimum and median daily streamflow around 1970, and a less significant mixed pattern of increases and decreases in annual maximum daily streamflow. These changes in annual streamflow statistics primarily occurred in the eastern U.S. In addition, the streamflow increases appear as a step change rather than as a gradual trend and coincide with an increase in precipitation. *INDEX TERMS:* 1860 Hydrology: Runoff and streamflow; 1833 Hydrology: Hydroclimatology; 1699 Global Change: General or miscellaneous. **Citation:** McCabe, G. J., and D. M. Wolock, A step increase in streamflow in the conterminous United States, *Geophys. Res. Lett.*, *29*(24), 2185, doi:10.1029/2002GL015999, 2002.

1. Introduction

[2] Climate model simulations using enhanced greenhouse forcing generally indicate widespread increases in precipitation and runoff, an outcome frequently cited as representing an intensified or accelerated hydrologic cycle [*Cubasch et al.*, 2001; *Milly et al.*, 2002]. The importance of an intensified hydrologic cycle stems from the possibility that it could lead to an increase in extreme hydrologic events, such as floods [*Milly et al.*, 2002]. Given the interest in relations between the greenhouse effect and an intensified hydrologic cycle, several studies have examined temporal changes in streamflow characteristics during the latter half of the twentieth century. This is a time period when the concentrations of atmospheric greenhouse gases increased significantly and when many streamgages provide flow data. *Lettenmaier et al.* [1994] examined trends in annual and monthly streamflow across the conterminous United States (U.S.) and found positive trends for a large proportion of the streams analyzed. *Lins and Slack* [1999] also analyzed streamflow in the conterminous U.S. and found statistically significant positive trends mostly in low and moderate streamflows; they found only a few positive trends in high streamflows. *Douglas et al.* [2000] also detected trends in low flows but not in floods. In contrast, *Groisman et al.* [2001] reported increases in high streamflow in the conterminous U.S., particularly in the eastern U.S.

[3] Most studies of historical changes in streamflow have made use of a non-parametric statistical trend test, such as Kendall's tau. A statistically significant result generally is interpreted to indicate a monotonic trend [*Helsel and Hirsch*, 1992]. Previous research has not demonstrated, however, whether commonly used statistical tests for trends can distinguish a gradual monotonic change from an abrupt "step" change. The distinction between a gradual trend and a step change is important, particularly for climatic-change impact studies. A gradual change usually is expected to continue into the future; step changes inherently are thought of as less predictable unless the cause for the abrupt change is known.

[4] The objective of this study is to clarify the nature of temporal changes in streamflow in the conterminous U.S. during the latter half of the twentieth century. An additional objective is to determine if the changes in streamflow are better characterized as a gradual change or a step change.

2. Data

[5] Daily streamflow for 400 sites in the conterminous U.S. with complete data for the 1941–1999 period were used in this study. These sites were chosen from the Hydro-Climatic Data Network (HCDN) [*Slack and Landwehr*, 1992]. HCDN sites are relatively free of anthropogenic influences and streamflow measured at these sites is considered to be natural. The 400 sites chosen represent a wide range of physiographic regions across the conterminous U.S.

[6] For each streamgage, minimum, median, and maximum daily streamflow were computed for each year of the 1941–1999 period. This provided three sets of time-series data (one for minimum daily streamflow, one for median daily streamflow, one for maximum daily streamflow) at each site. These data sets were used to determine how the magnitudes of the minimum, median, and maximum daily streamflow values changed over time in the conterminous U.S.

[7] In addition, the 99th percentile flow value for the entire period of record was computed at each site. Then the number of days in each year that the 99th percentile flow value occurred or was exceeded was counted. These data were used to determine how the frequency of high flow days changed during the 1941–1999 time period.

3. Analyses and Results

[8] Two approaches were used to evaluate temporal changes in annual streamflow statistics during the period 1941–1999. The first approach is based on an analysis of standardized departures, and the second approach relies on a

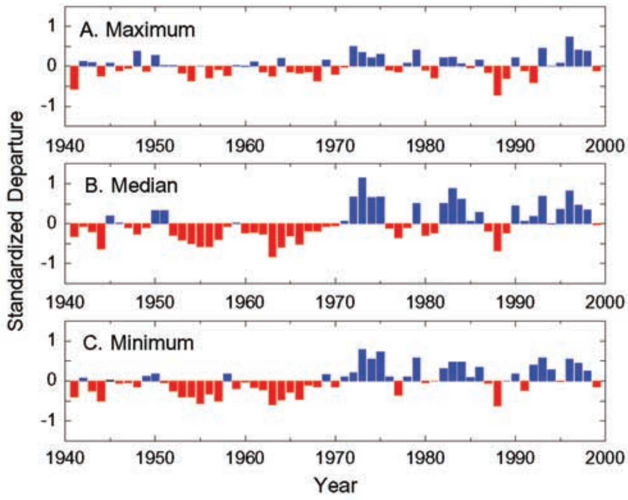

Figure 1. Mean standardized departures of annual (a) maximum, (b) median, and (c) minimum daily streamflow for 400 sites in the conterminous United States, 1941–1999.

conventional trend test. Both methods analyze the 400 sites collectively; that is, inferences based on the analyses are relevant to the conterminous U.S. taken as a whole, rather than for a specific location.

3.1. Standardized Departures Analysis

[9] Standardized departures of annual streamflow statistics (i.e., annual minimum, median, and maximum daily streamflow) for each site were computed by subtracting the respective long-term (1941–1999) mean from the flow values for each site and then dividing by the respective standard deviation. These standardized departures then were averaged for all 400 sites (Figure 1). For all of the streamflow statistics, the departures indicate a shift around 1970 from primarily negative departures (red) to primarily positive departures (blue). The standardized departure values are lower in magnitude for annual maximum daily streamflow compared to the annual minimum and median daily streamflow. The visual pattern of temporal variability in the streamflow statistics appears to be an abrupt increase in the streamflow regime near 1970, rather than a gradual increasing trend throughout the entire time period.

[10] Student's t-tests were used to identify sites with significant differences in mean annual daily streamflow statistics between the 1941–1970 and the 1971–1999 periods. Results indicate that there were few sites (11 percent of the 400 sites) with significant ($p \leq 0.05$) differences in mean annual maximum daily streamflow between the two time periods. In contrast, almost half (48 percent) of the sites had significant differences in both mean annual minimum and median daily streamflow between 1941–1970 and 1971–1999. The sites with significant increases in annual minimum and median daily streamflow statistics are located mostly in the eastern U.S. (east of 100 degrees west longitude). Only a few sites had decreases in any of the annual streamflow statistics.

[11] Although the Student's t-tests indicated that the magnitude of the largest annual streamflow events changed at only 11 percent of the sites, the potential that the frequency of high flow events changed at more sites was evaluated. This possibility was evaluated by comparing the mean frequency of the 99th percentile (or higher) flow (calculated for the 59-year period 1941–1999) during 1941–1970 with the mean frequency during 1971–1999 at all sites. Student's t-tests show that only about 17 percent of the sites had significant increases, and only about 2 percent of the sites had significant decreases.

[12] The percentage of sites with increases in annual minimum and median daily streamflow statistics in the eastern U.S. is consistent with the results of previous research [*Lins and Slack*, 1999; *Douglas et al.*, 2000]. The small percentage of sites with increases in annual maximum daily streamflow statistics also is in agreement with the results of *Lins and Slack* [1999] and *Douglas et al.* [2000]. However, it differs with the results presented by *Groisman et al.* [2001] who reported a significant increase in high streamflow in the conterminous U.S. The discrepancy in the results for high streamflows among the studies is likely due to differences in methodologies.

3.2. Trend Tests

[13] The time series from each site was evaluated for trends using Kendall's tau [*Press et al.*, 1986]. Kendall's tau is a non-parametric correlation statistic that is less sensitive to outliers than are parametric statistics such as Pearson's correlation coefficient. Kendall's tau was used to evaluate trends in the streamflow data by examining correlations between time and the streamflow statistics.

[14] Multiple trend tests were computed for all sites by varying the beginning date and ending date analyzed. The multiple trend tests were computed for all possible periods of at least 10 years in length during the 1941–1999 period. The number of sites with significant ($p \leq 0.05$) increasing or decreasing trends for each time period was counted. The counts were then plotted against the beginning and ending years of each period analyzed (Figure 2).

[15] Results of this analysis indicate relatively few increasing or decreasing trends in annual maximum daily streamflow, regardless of the beginning and ending years (Figure 2a). For all of the periods analyzed, the maximum number of sites with significant decreases in annual maximum streamflow is 50 (13 percent), and the maximum number of sites with significant increases in annual maximum streamflow is 60 (15 percent). In contrast, there is a large number of sites with increasing annual minimum and median daily streamflow statistics for some time periods (Figures 2b and 2c). The maximum number of sites with increases in annual minimum streamflow is 202 (51 percent), and the number of sites with increases in annual median streamflow is 219 (55 percent).

[16] The number of sites with increasing trends is dependent on the time period analyzed (Figure 2). Large numbers of sites with increasing trends in annual minimum and median streamflow are found for periods with a beginning year before 1970 and an ending year after 1970. In particular, periods with a beginning year in the mid-1950s and an ending year after 1970 include many sites with significant increasing trends. The mid-1950s was one of the driest periods in the conterminous U.S. and years after 1970 were generally wetter than average (Figure 1). The sensi-

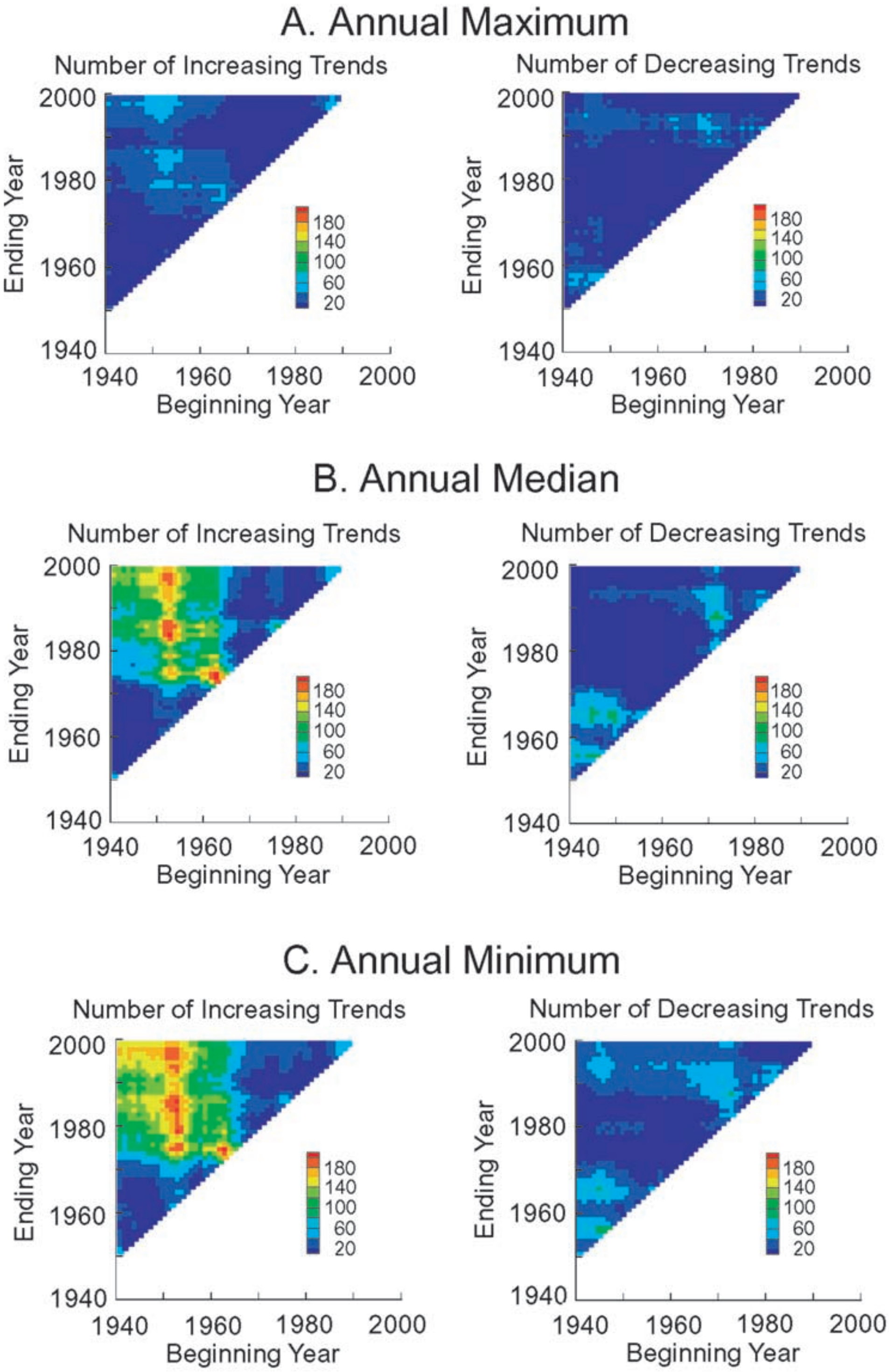

Figure 2. Number of sites with significant ($p \leq 0.05$) increasing and decreasing trends in annual (a) maximum, (b) median, and (c) minimum daily streamflow for various periods at least 10 years in length during 1941–1999.

tivity of the trend results to time periods with beginning dates before 1970 and ending dates after 1970 suggests that an abrupt change in streamflow around 1970 is the dominant feature of temporal changes during the 1941–1999 time period. A monotonic trend test such as Kendall's tau cannot distinguish a gradual change from an abrupt change in a single data sequence. However, the temporal pattern of Kendall's tau for many time periods does support the hypothesis of a step change rather than a gradual change.

[17] *Douglas et al.* [2000] and *Lettenmaier et al.* [1994] show how spatial cross-correlation of streamflow data measured at multiple streamgages reduces the number of independent sites and thus the degrees of freedom for statistical tests. This effect is especially important for

statistical tests comparing regional streamflow as done by *Douglas et al.* [2000]. Although spatial cross- correlation of streamflow reduces the effective number of independent samples in this study, it does not affect the results because we do not compare aggregated streamflow among regions. In the analyses presented in this paper, streamflow is statistically analyzed at streamgaging sites, and the number of sites with significant trends or changes is counted. Consideration of spatial cross- correlation would reduce the number of independent sites, but the relative percentages of sites with significant trends would remain the same.

[18] The increases in annual streamflow statistics around 1970 are coincident with increases in precipitation in the eastern U.S. [*Karl and Knight*, 1998]. For example, the correlation between annual precipitation averaged for the climate divisions of the conterminous U.S. [*Karl and Riebsame*, 1984; *Karl et al.*, 1986] and standardized departures of annual median daily streamflow averaged for the U.S. is 0.77. On a seasonal basis, *Karl and Knight* [1998] reported that precipitation increases in the conterminous U.S. have been greater during the fall season than during other seasons. This point is important because minimum streamflows in the conterminous U.S. occur most frequently during September and October, and median streamflows are most frequent in November, December, and January. Thus, the timing of the precipitation increase reported by *Karl and Knight* [1998] is consistent with the increase in minimum and median streamflows reported here.

4. Summary and Conclusions

[19] Standardized departures analysis and trend tests of 59 years of streamflow measurements in the U.S. indicate that (1) there are relatively few sites with significant changes in annual maximum daily streamflow as compared to annual minimum and median daily streamflow; (2) most changes in streamflow statistics appear as increases in annual minimum and median daily streamflow in the eastern U.S.; (3) the frequency of 99th percentile streamflows appears to have increased for only a few sites; and (4) all of the increases in annual streamflow statistics appear to have been the result of a step increase around 1970 rather than as a gradual trend. The identification of an abrupt increase in streamflow rather than a gradual increasing trend is important because the implications of a step change are different from those of a gradual trend. The interpretation of a gradual trend is that the trend is likely to continue into the future, whereas the interpretation of a step change is that the climate system has shifted to a new regime that will likely remain relatively constant until a new shift or step change occurs.

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