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Increasing U.S. Streamflow Linked to Greenhouse Forcing

Although considerable effort has gone into assessing and projecting climatic change, continental-scale analyses of trends in only one component of the hydrologic cycle—precipitation—have been described. With few exceptions [see *Zektser and Loaiciga*, 1993], assessments of temporal variations in runoff, evaporation, and soil water storage have been neglected, to some degree because of a lack of adequate observational data.

On a regional basis, have there been any changes in seasonal patterns of streamflow in the United States? If so, are these changes consistent with documented variations in other hydroclimatic variables? To answer these questions, we examined a set of climate-sensitive streamflow data recently collected by the U.S. Geological Survey. This data set covers the years 1941-1988 and presents data from 559 gaging stations across the conterminous United States.

We found that increasing trends in monthly streamflow during the past 5 decades across most of the conterminous United States support the hypothesis that enhanced greenhouse forcing produces an enhanced hydrologic cycle, at least during autumn and winter months.

The records analyzed are a subset of the USGS Hydro-Climatic Data Network (HCDN), a CD-ROM collection of streamflow observations designed to provide a national hydrological data set that is sensitive to climatic variability and change [*Slack et al.*, 1993]. This data set is particularly useful in answering questions of variability in the runoff phase of the hydrologic cycle.

The HCDN collects data only in basins where there has been no overt adjustment of "natural" streamflow through regulation or diversion. Although the basins may be subject to some degree of human activity, such as land use changes, these changes are not large enough to affect the monthly mean discharge. The HCDN consists of 1,659 sites throughout the United States and its territories and contains a total of 73,231 water years of daily mean discharge values. Several criteria were used to evaluate whether station records were acceptable for inclusion in the HCDN and ensure that any trends detected in the records are due to actual changes in streamflow rather than to human activities or changes in measurement methods.

The Analysis

We analyzed changes in monthly regional streamflow using a combination of principal components analysis and the nonparametric Mann-Kendall test. We followed the principal components procedure used by *Barnston and Livezey* [1987] that defined persistent patterns in monthly mean 700-mb geopotential height. We performed a separate orthogonally rotated principal components analysis (RPCA) for each month of the year. Each of the twelve streamflow matrices is dimensioned 48 x 559 (48 years of record at 559 gage sites). In our study, these components are uncorrelated linear combinations of the spatial streamflow data that result in coherent and persistent monthly streamflow patterns.

When grouped collectively, we found that eleven "regional" patterns appeared persistently; see Table 1. Most of these patterns persist throughout the year. A few, however, appear primarily during the cooler months or only during the warmer months.

Monotonic trends in these regional streamflow regimes were evaluated using the Mann-Kendall test. In nine of the eleven regional streamflow regimes, statistically significant increases were observed in some months over the entire period. No decreases were observed. These trends are noted in Table 2. Two findings are immediately apparent. First, unimpaired streamflow has increased in nearly all regions of the conterminous United States since the early 1940s. Second, with one exception, all of the observed positive trends occurred in autumn and winter. The exception occurred in New England in August. Increasing trends are evident in the Upper Mississippi (September-December), Ohio Valley (September-November), Southern Plains (November-January), Far West (September-November), Northeast (October), Eastern/Mid-Atlantic (December), South Atlantic/Gulf (November and February), and Rocky Mountain (January-February) regions. No other trends were evident in any region from April through August.

These findings are also consistent with several recent studies of streamflow variability in the western United States. *Wahl* [1992]

Table 1. Patterns Defined by the Rotated Principal Components of Mean Monthly Streamflow

	All Seasons							Primarily Cold		Warm	
Month	UM*	SAG	FW	OV	WO	NE	EMA	SP	NEW	RM	MM
Oct	**1**(12.65)	**4**(7.47)	**7**(5.64)	**6**(5.84)	**5**(7.14)	**2**(9.78)	**3**(7.90)	**8**(5.52)			
Nov	**1**(13.64)	**2**(11.19)	**6**(6.35)	**5**(6.69)	**4**(7.00)	**3**(9.35)		**7**(4.83)	**9**(3.46)		
Dec	**2**(14.46)	**5**(6.49)	**4**(7.06)		**6**(5.95)	**3**(7.79)	**1**(16.14)	**7**(4.86)	**9**(3.36)		
Jan	**3**(10.62)	**7**(4.47)	**4**(7.60)	**2**(12.49)	**8**(4.32)		**1**(16.65)	**5**(5.82)	**6**(4.62)		
Feb	**5**(8.00)	**7**(5.15)	**6**(5.47)	**1**(11.88)	**4**(8.15)	**3**(9.50)	**2**(11.83)	**8**(4.92)			
Mar	**1**(10.97)	**7**(5.51)	**2**(10.57)	**4**(10.49)	**8**(4.51)	**5**(6.43)	**3**(10.57)	**6**(5.80)			
Apr	**3**(8.56)	**5**(6.76)	**7**(5.26)	**4**(7.62)		**8**(4.14)	**1**(15.54)	**6**(6.42)	**10**(3.44)	**2**(9.15)	
May	**2**(8. 85)	**4**(7.38)	**6**(6.79)	**3**(8.26)	**7**(6.20)	**5**(6.87)	**1**(10.61)			**8**(5.14)	
Jun	**3** (8.68)	**4**(6.98)	**5**(6.65)	**7**(5.76)	**1**(9.50)	**2**(9.26)	**6**(6.00)			**9**(4.11)	**8**(5.63)
Jul	**7**(6.49)	**6**(6.85)	**3**(7.90)	**4**(7.42)	**2**(8.28)	**1**(8.34)	**5**(7.20)			**8**(4.49)	
Aug	**4**(7.39)	**2**(8.04)	**5**(7.15)	**6**(6.18)	**3**(7.58)	**1**(8.05)			**9**(3.75)		**7**(5.04)
Sep	**2**(7.94)	**6**(6.09)	**5**(6.81)	**4**(7.16)	**7**(5.67)	**3**(7.33)	**1**(8.40)	**10**(3.52)		**9**(3.61)	**8**(5.42)

Mode numbers and the percentages of variance (in parentheses) are shown.

* Region abbreviations: UM, Upper Mississippi valley; SAG, South Atlantic/Gulf coastal; FW, Far West (centered on northern California and western Nevada); OV, Ohio Valley; WO, Western Opposition (sign opposition in contemporaneous anomalies in Pacific Northwest and arid Southwest); NE, Northeast; EMA, Eastern/Mid-Atlantic; SP, Southern Plains; NEW, New England; RM, Rocky Mountain; MM, Middle Mississippi valley. Missing values in the table represent months when a regional pattern was not evident in the principal component analysis.

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Table 2. Trends in Streamflow by Region and Month

Region	Month	PC Mode Number	tau	p-value	slope* (units per year)
Upper Mississippi	Sep	2	0.20	0.048	0.165
	Oct	1	0.31	0.002	0.303
	Nov	1	0.29	0.004	0.305
	Dec	2	0.30	0.003	0.367
Eastern/Mid-Atlantic	Dec	1	0.20	0.048	0.233
Northeast	Oct	2	0.20	0.042	0.200
Ohio Valley	Sep	4	0.27	0.006	0.227
	Oct	6	0.25	0.011	0.223
	Nov	5	0.21	0.035	0.223
South Atlantic/Gulf	Nov	2	0.20	0.046	0.177
	Feb	7	0.25	0.013	0.151
Far West	Sep	5	0.21	0.035	0.165
	Oct	7	0.23	0.021	0.165
	Nov	6	0.23	0.022	0.171
Southern Plains	Nov	7	0.28	0.005	0.196
	Dec	7	0.24	0.015	0.167
	Jan	5	0.20	0.044	0.121
New England	Aug	9	0.23	0.022	0.128
Rocky Mountain	Jan	10	0.35	0.000	0.196
	Feb	9	0.23	0.019	0.138

Only those regions (i.e., principal components) having a p-value (attained significance level) are listed.

*Slope expressed in the dimensionless units of principal component scores.

and *Dettinger et al.* [1994] report that, although spring annual streamflow decreased during the past 50-80 years, this is not due to a decrease in spring season discharge. Rather, as is pointed out in *Aguado et al.* [1992], the decrease of total annual streamflow from April through July corresponds with an increase in autumn to winter streamflow. These findings are consistent with the Intergovernmental Panel on Climate Change (IPCC) general circulation model (GCM)-based scenarios that posit winter precipitation increases in the central United States with an enhanced greenhouse effect.

This agreement is somewhat surprising because earlier analysis of 20th century precipitation in the central United States found no statistically significant trends in winter.

The IPCC findings were based on simulations from the Canadian Climate Centre, the Geophysical Fluid Dynamics Laboratory, and the United Kingdom Meteorological Office general circulation models. Projected winter precipitation changes from these three models for the central United States were 0, 15, and 10% percent respectively. However, confidence in the three estimates was reported to be low.

These results lead us to agree with *Karl et al.* [1991] that while some of the IPCC projections are roughly consistent with observations, there are other important inconsistencies. One possible explanation for the differences between Karl's finding of no increases in winter-season precipitation and our increasing winter streamflow is that there may have been a decrease in evaporation, which would occur if there were an increase in cloudiness even if temperature and precipitation did not change. Such increases were reported across the United States between 1950 and 1988 [*Angell*, 1990]. The streamflow and cloudiness data are also consistent with the trend toward lower daily maximum temperatures (and therefore less evaporation) that occurred across the United States from 1948-1987.—*Harry F. Lins, U.S. Geological Survey, Reston, Va.; and Patrick J. Michaels, University of Virginia, Charlottesville*

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