Recent trends in USA streamflow: Implications for the water cycle

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We use a subset of ∼1000 United States Geological Survey stream gauges primarily from small, minimally disturbed watersheds to estimate annual streamflow per unit area since ∼1920 on a uniform grid over the conterminous United States. We find that although streamflow has indeed increased over this period taken as a whole, this increase has not been uniform in time but concentrated over a few years around 1970, when precipitation increased. Since the early 1990s, both precipitation and streamflow show nonsignificant declining trends. Multiple regression of streamflow against precipitation, temperature and CO_2 suggests that higher CO_2 levels may increase streamflow, presumably due to the physiological plant response to CO_2, but that this positive response is more than offset by the concomitant increasing evaporation due to global warming, so that the net impact of greenhouse gas emissions has been to reduce streamflow. The suppression of plant transpiration through higher CO_2 levels seems to be particularly important for sustaining high streamflow in the Great Plains, where precipitation is concentrated during the growing season.

Background

Uncertainties in the effect of greenhouse gas emissions on climate and life on earth cluster around water in its three phases – solid (glacier melting, Arctic amplification of warming via albedo feedback, sea level rise), vapor (as a greenhouse gas), and liquid (cloud feedbacks, for example). On the liquid side, large additional emissions of carbon from land plants and soils (carbon-climate feedback) could result if warming leads to more droughts (Fung et al. 2005; Friedlingstein et al. 2006). The drying impact of hotter summers could be offset, though, if warming also brings with it more rainfall. Labat et al. (2004) reported on trends in streamflow from several dozen large basins over 1925–1994, finding an increasing trend in streamflow and a significant positive correlation between yearly streamflow and yearly hemispheric temperature, both globally and over North America, meaning that increasing precipitation over land has more than compensated for the increased evaporation due to heating. High atmospheric CO_2 might also be contributing to higher streamflow by reducing the amount of water plants transpire per unit of carbon taken up (Gedney et al. 2006).

Previous analyses of the impact of climate on streamflow have been hampered by uncertainty over the impact of land-use change and water diversion and by poor quantification of measurement errors. We mapped annual streamflow over the conterminous USA based on stream gauge measurements in primarily small, minimally disturbed drainage basins from the United States Geological Survey (USGS) Hydro-Climatic Data Network (HCDN), using geostatistical methods to estimate the uncertainty in our estimates of areally integrated streamflow due to small-scale variability, missing data, and measurement error.

Methods

HCDN (Slack and Landwehr 1992) includes over 1,600 stream gauges chosen for being influenced over their period of record primarily by climatic variations rather than by land-use change or water diversion (Figure 1). We extended records past the original HCDN end date of 1988 if measurements continued to be collected by USGS, and then filled in missing years using regularized, iterative linear regression (Schneider 2001), which also provided an estimate of the correlations between streamflow time series.

Streamflow anomalies at nearby watersheds are correlated, with a correlation length scale of ∼700 km. Using the spatial correlation structure derived from the stream gauge network (Cressie 1993), we interpolated streamflow anomalies by year over the USA on a 1° grid, then scaled by climatological streamflow per unit area from Fekete et al. (2002) to map actual streamflow.

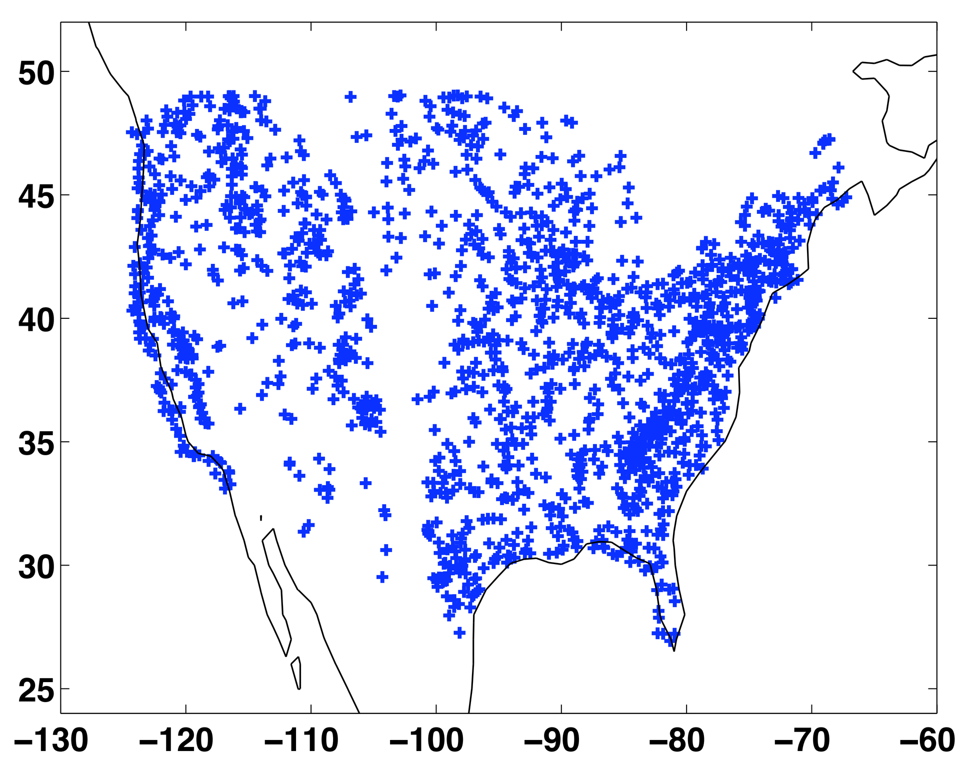

Figure 1. Locations of HCDN stream gauges.

Trends in streamflow

Total streamflow over the conterminous USA shows large variability from year to year, which can be smoothed by averaging over longer periods (Figure 2). Streamflow tended to increase over about 1940–1990, with most of the increase around 1970, but since then has stayed level or declined, despite increasing local and global temperatures. Fitting a linear trend in streamflow to various spans of years gives +0.57±0.22 mm/year per year for 1925–1994 (Labat et al.'s focus) and +0.43±0.17 for 1925–2007, but −2.3±2.2 for 1994–2007. When this recent period is taken into consideration, streamflow does not appear to increase with temperature.

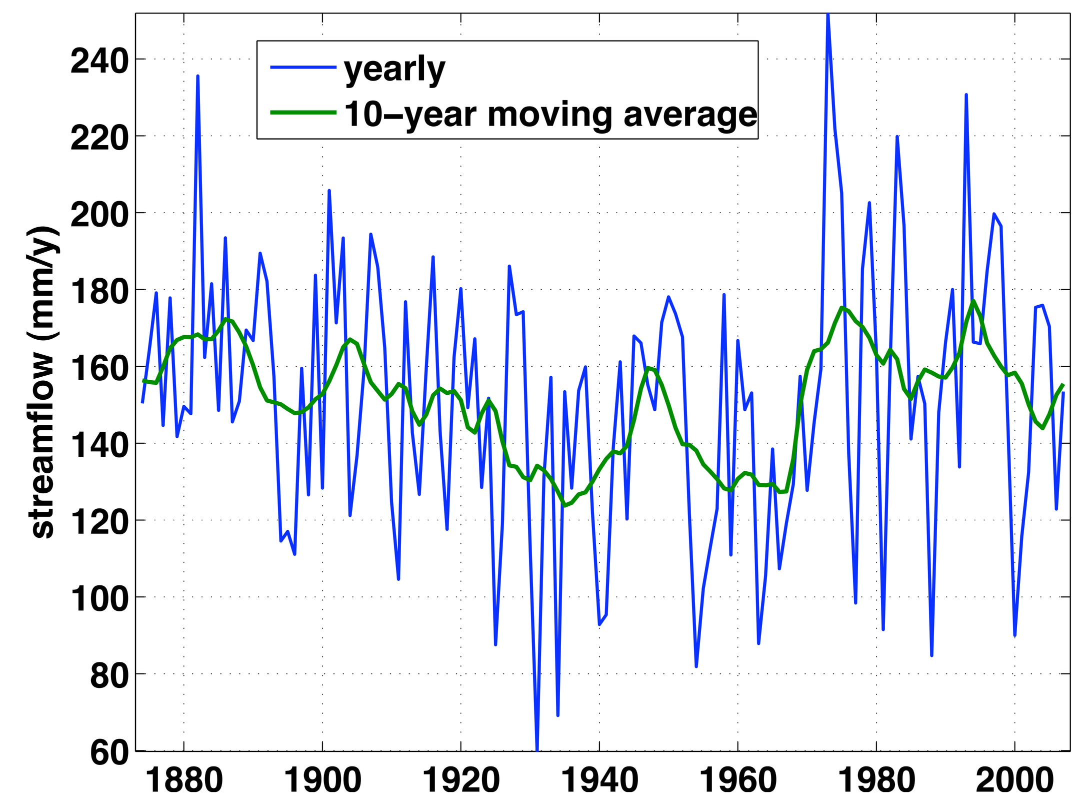

Figure 2. Estimated yearly streamflow since 1875 for the conterminous USA and its 10-year moving average. Values before ∼1920 are quite uncertain because relatively few stream gauge records are available from then.

Streamflow and precipitation

The main determinant of streamflow is precipitation, which shows the same increase around 1970 as streamflow. Figure 3 shows annual streamflow versus precipitation from the Global Historical Climate Network (Peterson and Vose 1997). Like streamflow, precipitation does not increase during the recent warming (Figure 4).

Streamflow is determined not only by the total amount of precipitation but also by its space-time distribution. Linear regression of streamflow vs. seasonal precipitation shows that a unit increase in winter (October-March) precipitation affects streamflow much more the same increase in summer precipitation. As well, a much greater fraction of precipitation is converted into streamflow in moist regions like the Northeast and the Cascades than in dry regions in the center and arid west, where almost all precipitation evaporates (Figure 5). The correlation of streamflow to annual precipitation is therefore weakest in the Great Plains, where the precipitation seasonality and antecedent soil moisture status may be equally important.

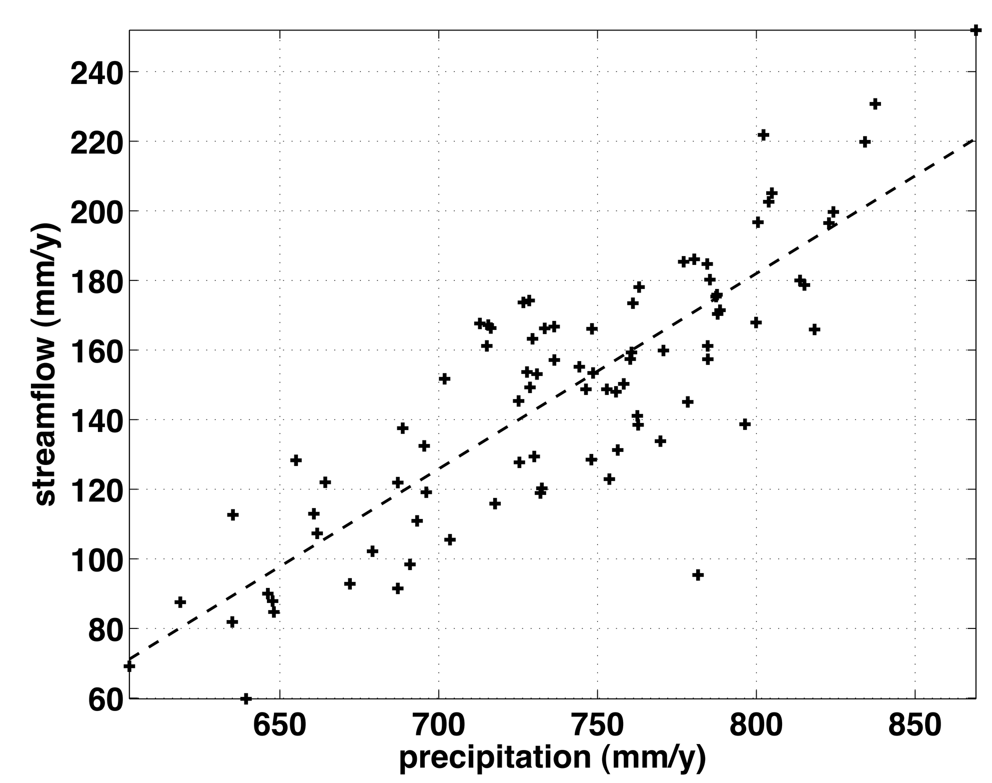

Figure 3. Scatterplot of annual streamflow vs. annual precipitation for the conterminous USA for 1920–2005. The least-squares trendline is shown ($R^2 = 0.70$; streamflow = $(0.56 \pm 0.04)*$precipitation – (267 ± 30) mm/y).

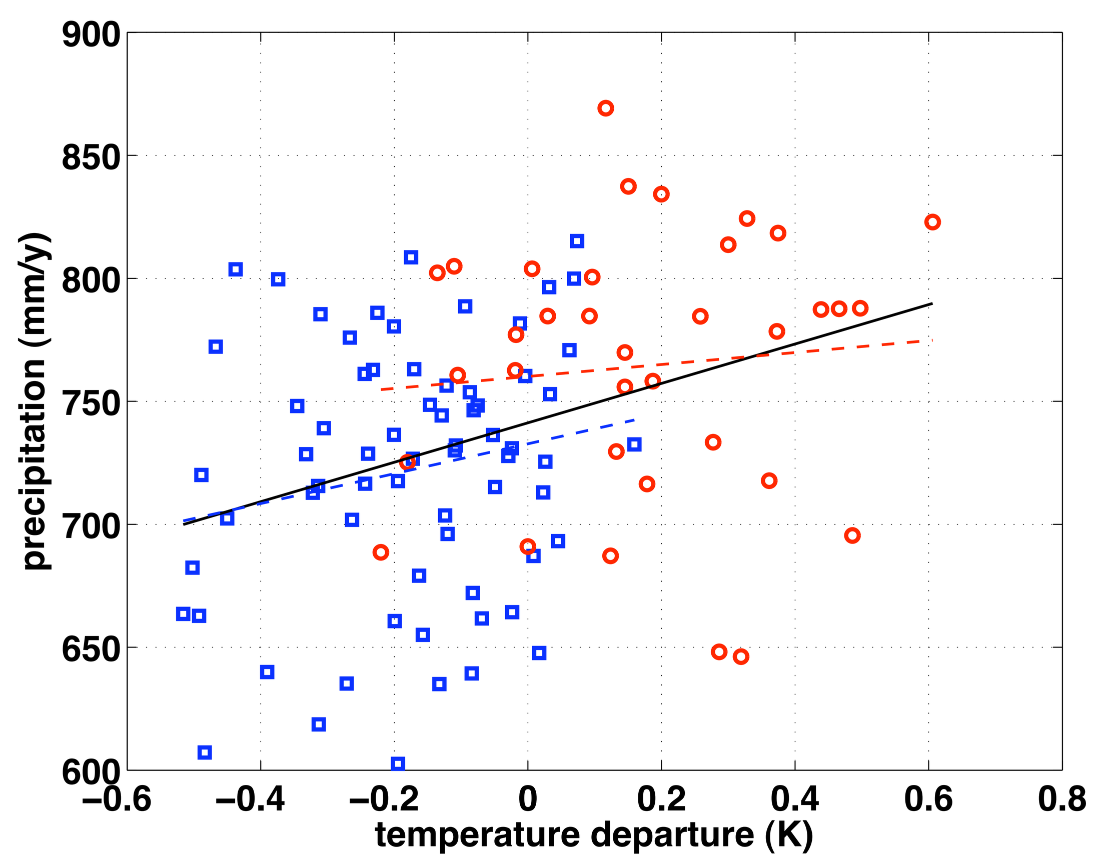

Figure 4. Annual global temperature (Jones et al. 2006) and conterminous USA precipitation, 1901–2005. Blue squares are years from 1901–1970, red circles are years from 1971–2005. The solid line is the least-squares regression line for the entire period, while the blue and red dashed lines are regression lines for the periods 1901–1970 and 1970–2005 respectively. While over the whole period precipitation is significantly, if weakly, correlated with temperature ($R^2 = 0.12$), the correlation vanishes after 1970.

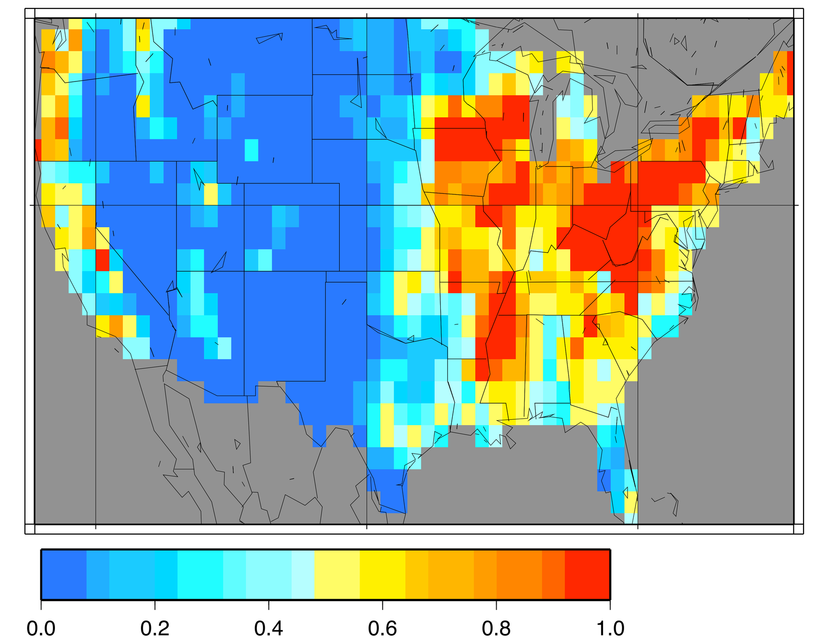

Figure 5. Regression coefficient of annual streamflow with precipitation, 1920–2005.

Streamflow, warming and CO_2

Part of the decline in streamflow since 1994 can be explained by warming, which increased evaporation while precipitation has not increased (Figure 6). Regressing streamflow against both CO_2 concentrations and temperature suggests that the physiological effect of CO_2 is to reduce plant transpiration and thus increase streamflow, but that for the most part this is more than offset by the role of greenhouse warming in accelerating evaporation and thus reducing streamflow and increasing water stress. An exception is in the Great Plains, where because precipitation is concentrated in the growing season the physiological CO_2 effect seems to dominate and streamflow has been increasing (Figure 6)

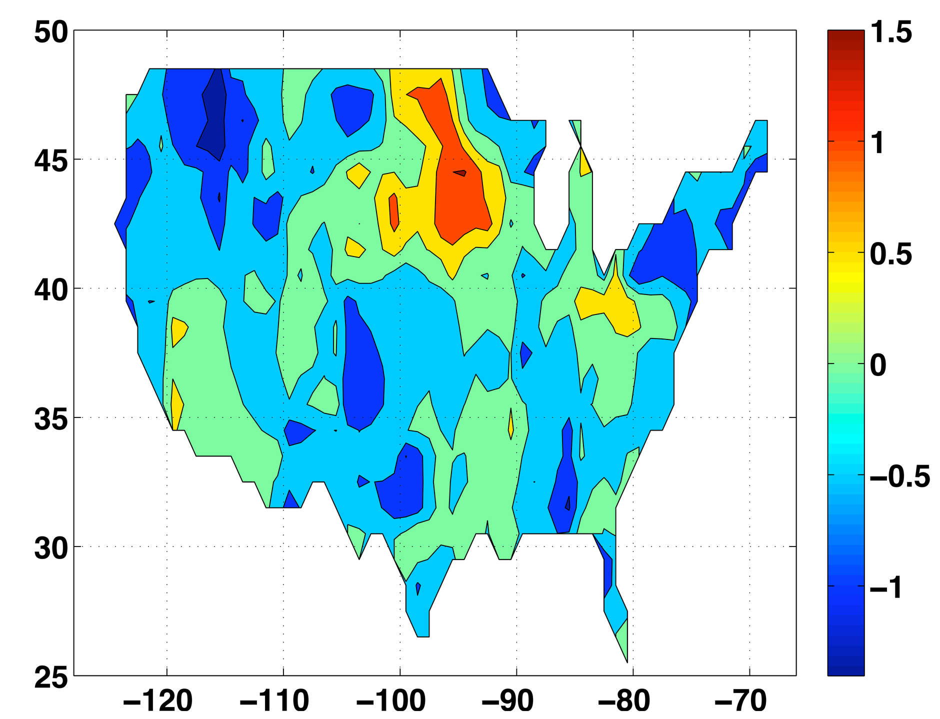

Figure 6. Regression coefficient of CO_2 level on annual streamflow in a multiple regression against precipitation and CO_2 (so that the CO_2 response includes the effect of greenhouse warming), 1920–2005. The units are streamflow standard deviations per 100 ppm CO_2. The standard error of the regression coefficient is about 0.3 SD / 100 ppm CO_2.

Conclusions

We find no consistent increase in USA streamflow with warming. We hypothesize that similar results hold for midlatitude land areas generally, but similar analyses of streamflow trends in other countries that have adequate measurements are needed to verify this. Our findings are consistent with theory and observations that under global warming precipitation tends to increase only in already-wet areas like the Intertropical Convergence Zone, while most land areas see decreases or no increases (Held and Soden 2006; Gu et al. 2007). Indeed, paralleling our finding of decreasing streamflow in the 1990s, the amplitude of the northern-hemisphere seasonal cycle in CO_2 concentration has stopped increasing since the early 1990s, interpreted as the result of dry summers restricting plant growth (e.g. Zeng et al. 2005; Buermann et al. 2007). Given that precipitation and streamflow have not increased thus far with warming, further worsening of drought over the USA looks likely for this century.

Acknowledgment

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