A hot, dry 21st century? Implications of recent trends in USA streamflow

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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 river runoff from several dozen large basins over 1925-1994, finding an overall increase in runoff with time and a significant positive correlation between yearly runoff 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.

Most previous analyses of the impact of climate on streamflow over decadal timescales have been limited by uncertainty over the impact of land-use change and water diversion and by poor quantification of measurement errors. We mapped annual runoff over the conterminous USA since 1920 based on stream gauge measurements in primarily small, minimally disturbed drainage basins from the US Geological Survey (USGS) Hydro-Climatic Data Network (HCDN), using geostatistical methods to estimate the uncertainty in our estimates of areally integrated runoff 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. Figures 1 and 2 show their space and time distribution. 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 covariance structure of streamflows. We divided observed streamflow by the drainage area to estimate annual runoff. Runoff anomalies at nearby watersheds are correlated, with an exponential correlation decay length of approx. 7°. This allowed us to estimate, using geostatistical interpolation (Cressie 1993), runoff anomalies by year over the USA on a 1° grid.

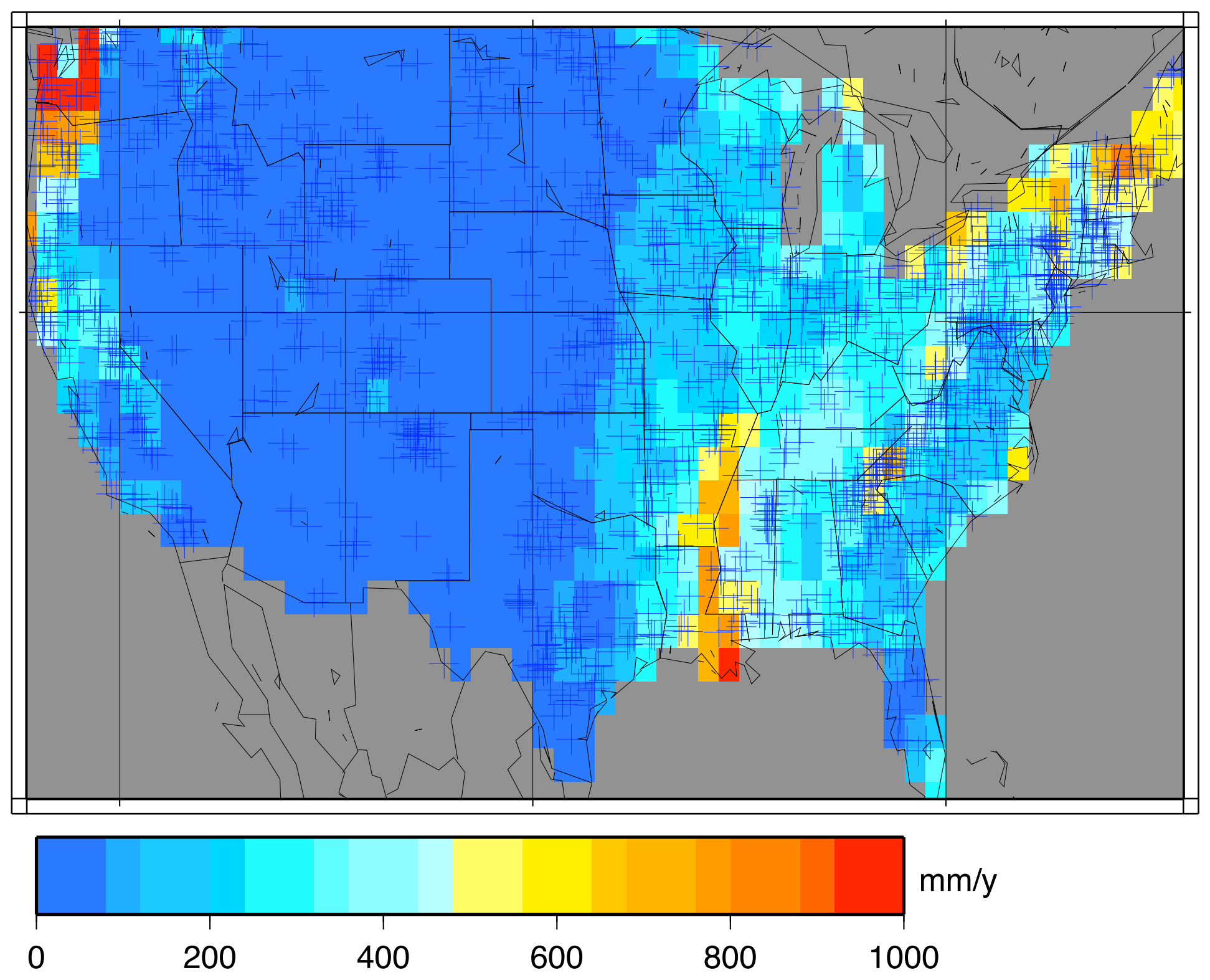

Figure 1. Distribution of mean annual runoff in the USA (Fekete et al. 2002). Crosses show the locations of stream gauges used.

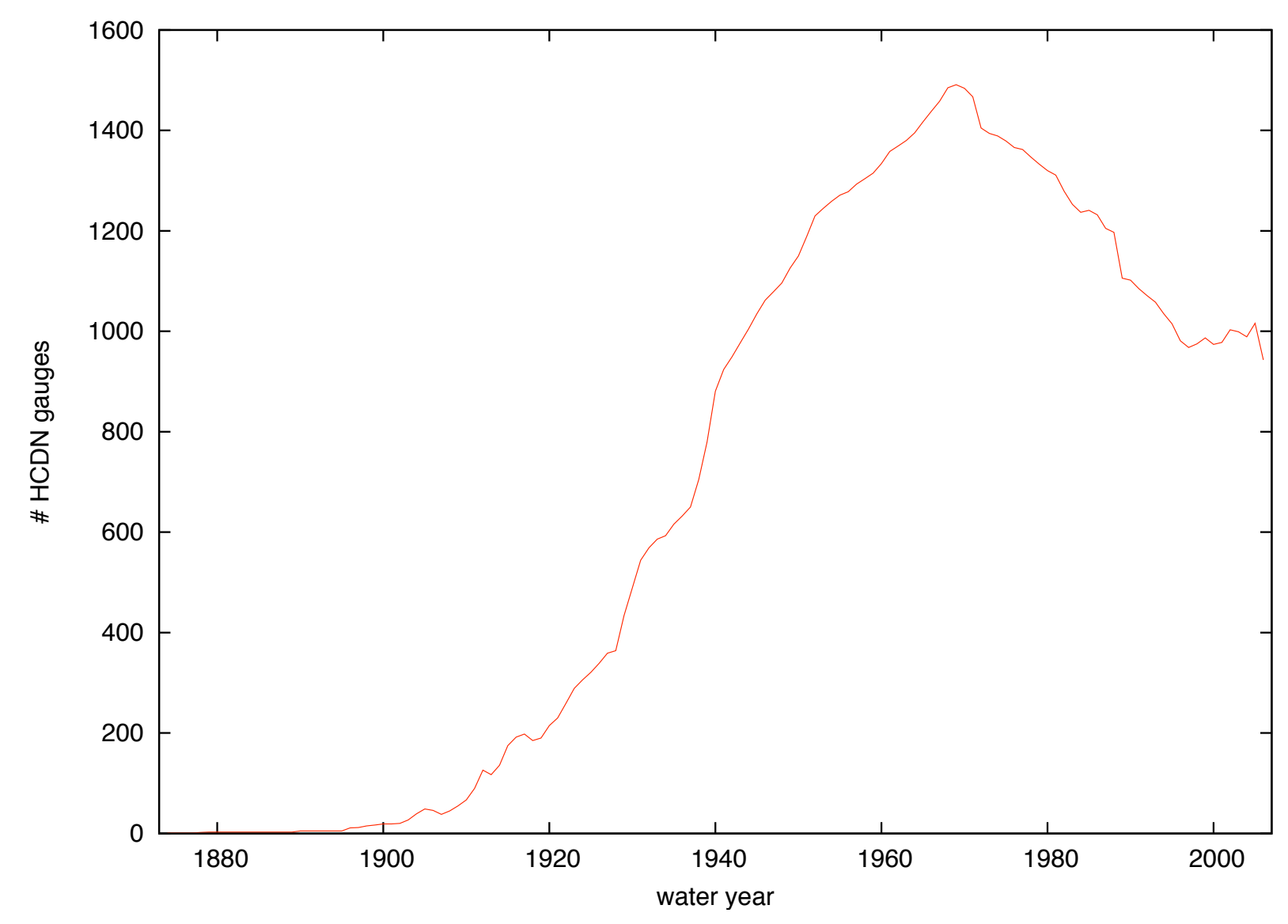

Figure 2. Reporting stream gauges per year.

Trends in streamflow

Mean runoff over the USA shows large variability from year to year, which can be smoothed by averaging over longer periods (Figure 3). Runoff tended to increase over about 1940–1990 but since then has stayed level or declined, despite increasing local and global temperatures. Fitting a linear trend in runoff to various spans of years gives +0.55±0.22 mm/year per year for 1925–1994 (Labat et al.'s focus) and +0.43±0.17 for 1925–2006, but —2.6±2.5 for 1994–2006 (Figure 3). When this more recent period is taken into consideration, no simple relationship between temperature and runoff appears to hold.

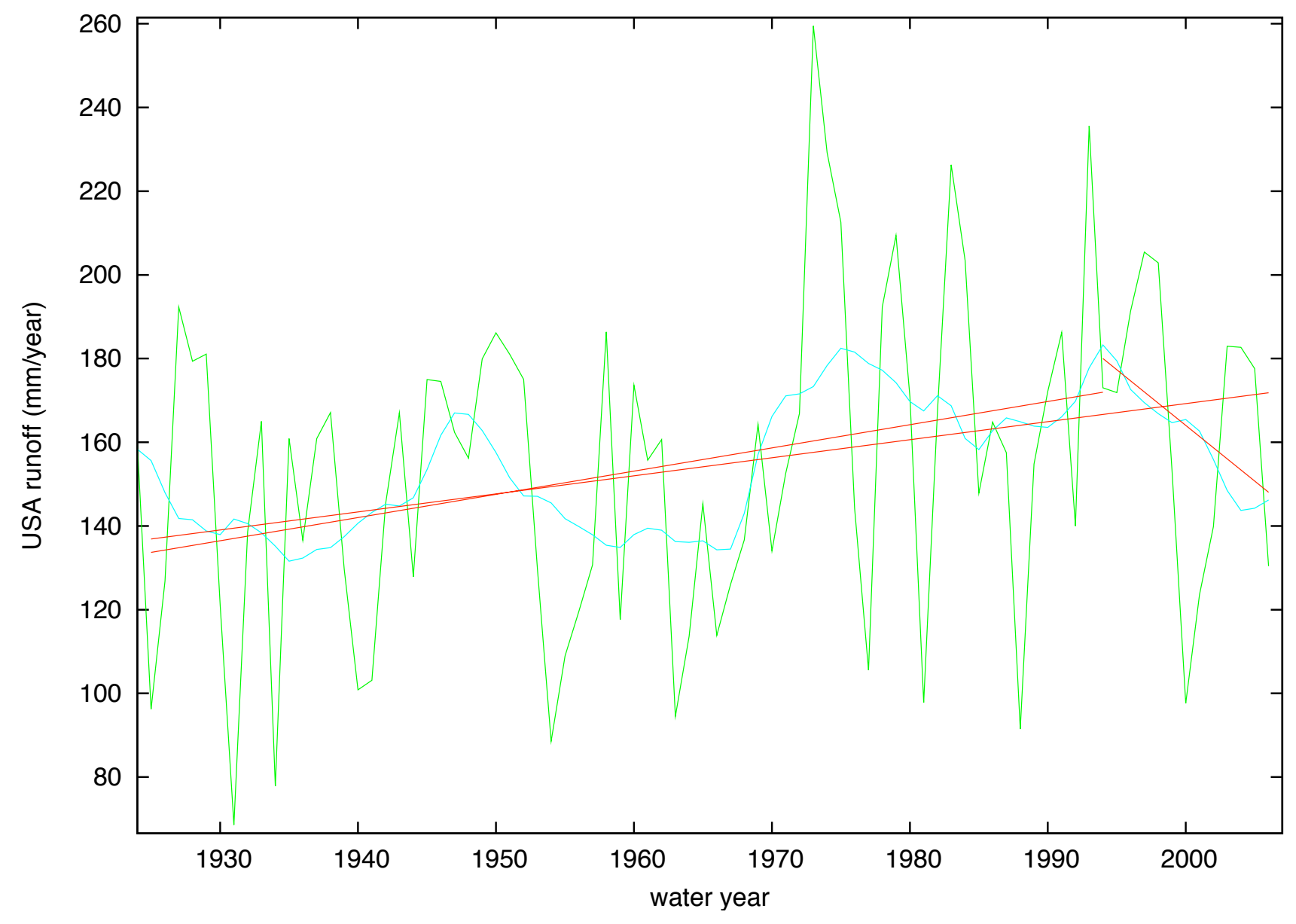

Figure 3. Estimated annual runoff from the conterminous USA (green line) and 10-year moving average (blue line), plus trendlines from linear regressions for the periods 1925–1994, 1925–2006, 1994–2006.

Streamflow and precipitation

The main determinant of streamflow is local precipitation. Figure 4 shows USA annual runoff versus USA precipitation from the Global Historical Climate Network (Peterson and Vose 1997). A close relationship to precipitation is seen both before 1994 (xs in Figure 4) and afterwards (squares in Figure 4).

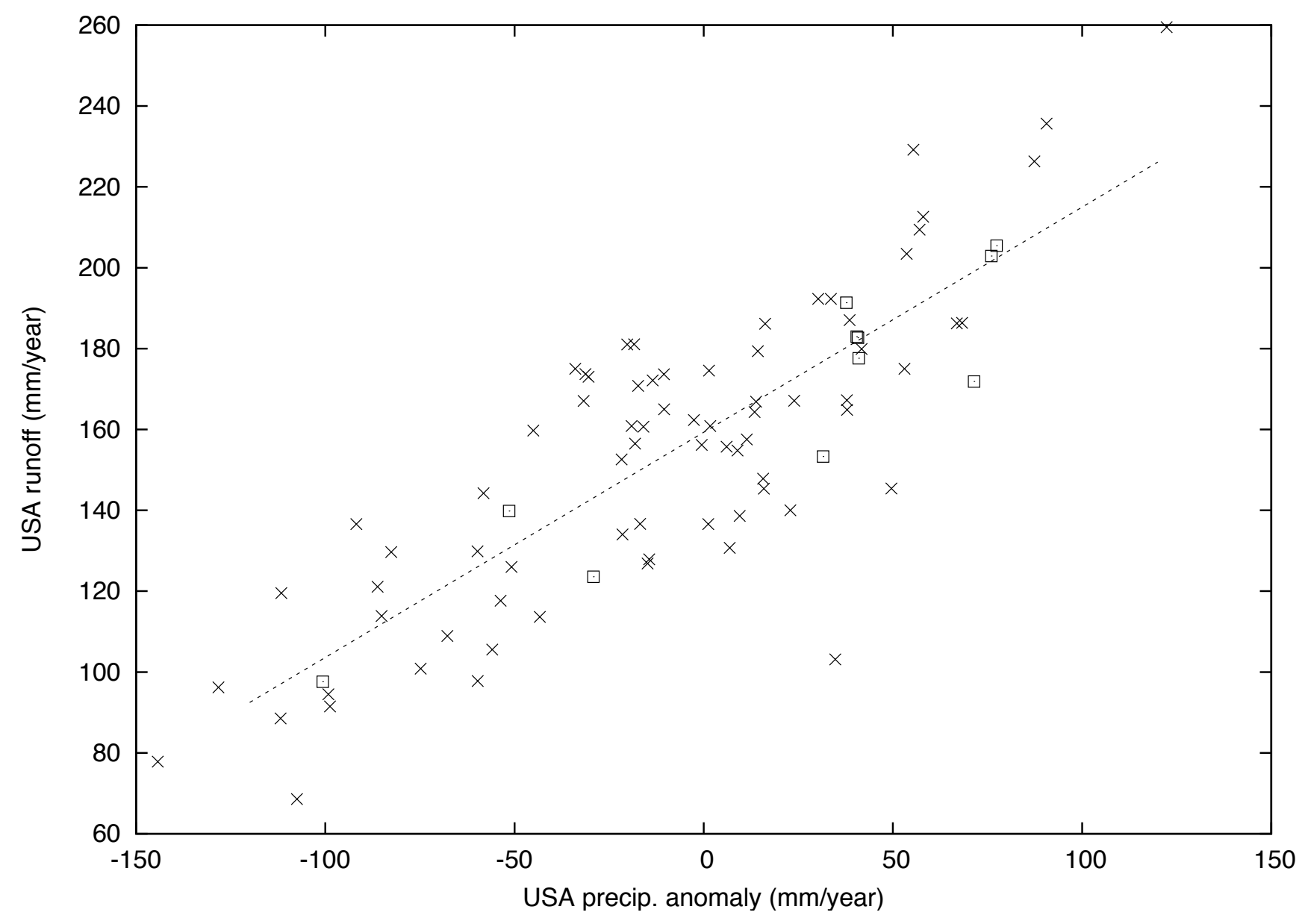

Figure 4. Scatterplot of annual runoff vs. annual precipitation for the conterminous USA for 1920-2005. Squares are years after 1994. The least-squares trendline is shown ($R^2 = 0.68$); its slope is 0.56.

Runoff is determined not only by the total amount of precipitation falling over the US but also by its space-time distribution. Linear regression of runoff vs. seasonal precipitation shows that a unit increase in winter (October-March) precipitation affects runoff much more the same increase in summer precipitation. As well, a much greater fraction of additional precipitation is converted into streamflow in moist regions like the Northeast and the Cascades than in dry regions like the Great Basin, where almost all precipitation evaporates (Figure 5). Whether changes in the distribution of precipitation contribute importantly to interannual variability in streamflow over the USA remains to be determined.

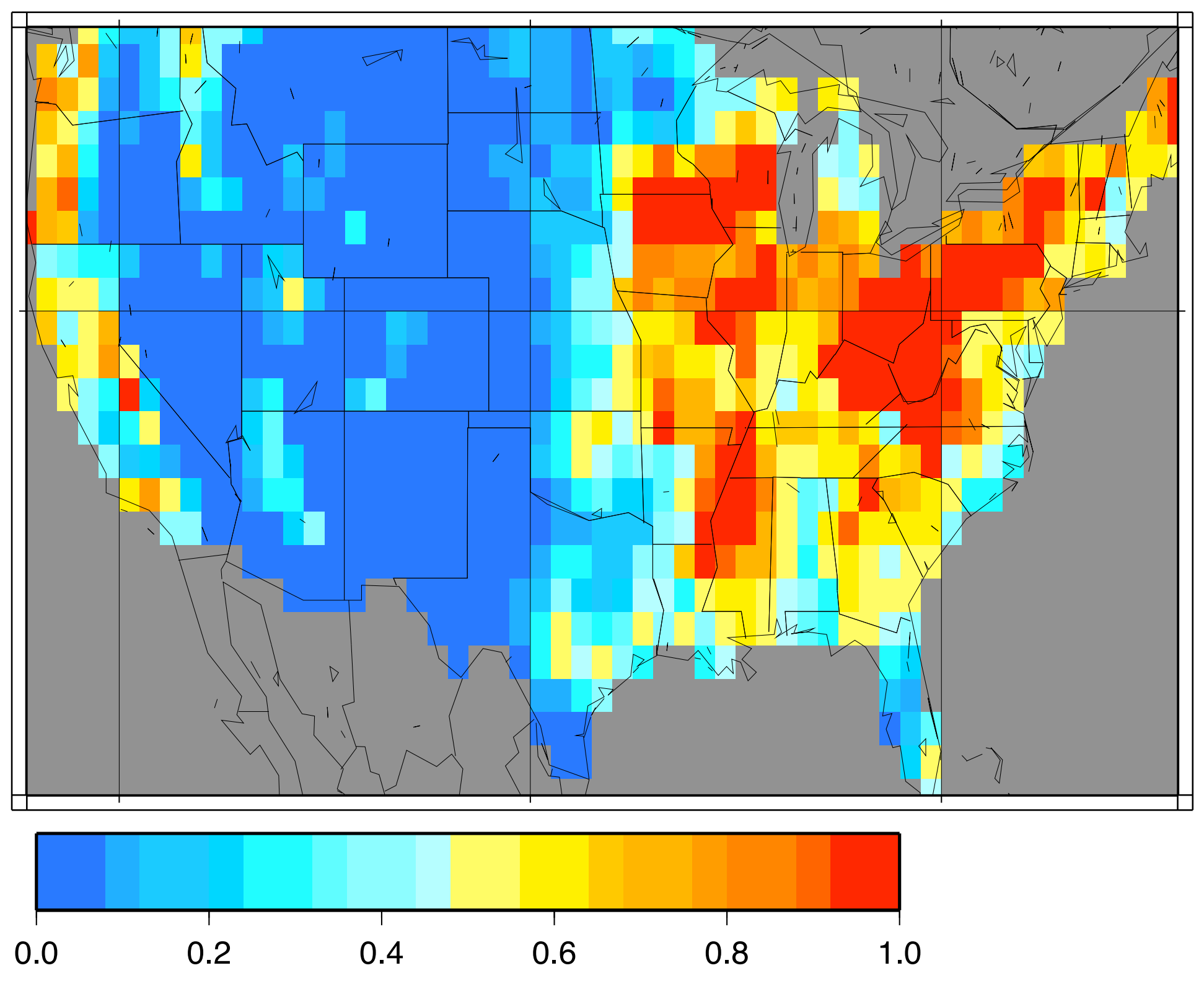

Figure 5. Regression coefficient of annual streamflow with precipitation, 1920-2005.

Streamflow and warming

Part of the decline in streamflow since 1994 can be explained by higher temperatures, which increased evaporation (Figure 6) while precipitation has not increased. This suggests that even if rising CO_2 concentrations are enabling plants to increase their water-use efficiency, as Gedney et al. (2006) have suggested, this is insufficient to offset the effect of greenhouse warming in accelerating evaporation and thus reducing streamflow and increasing water stress.

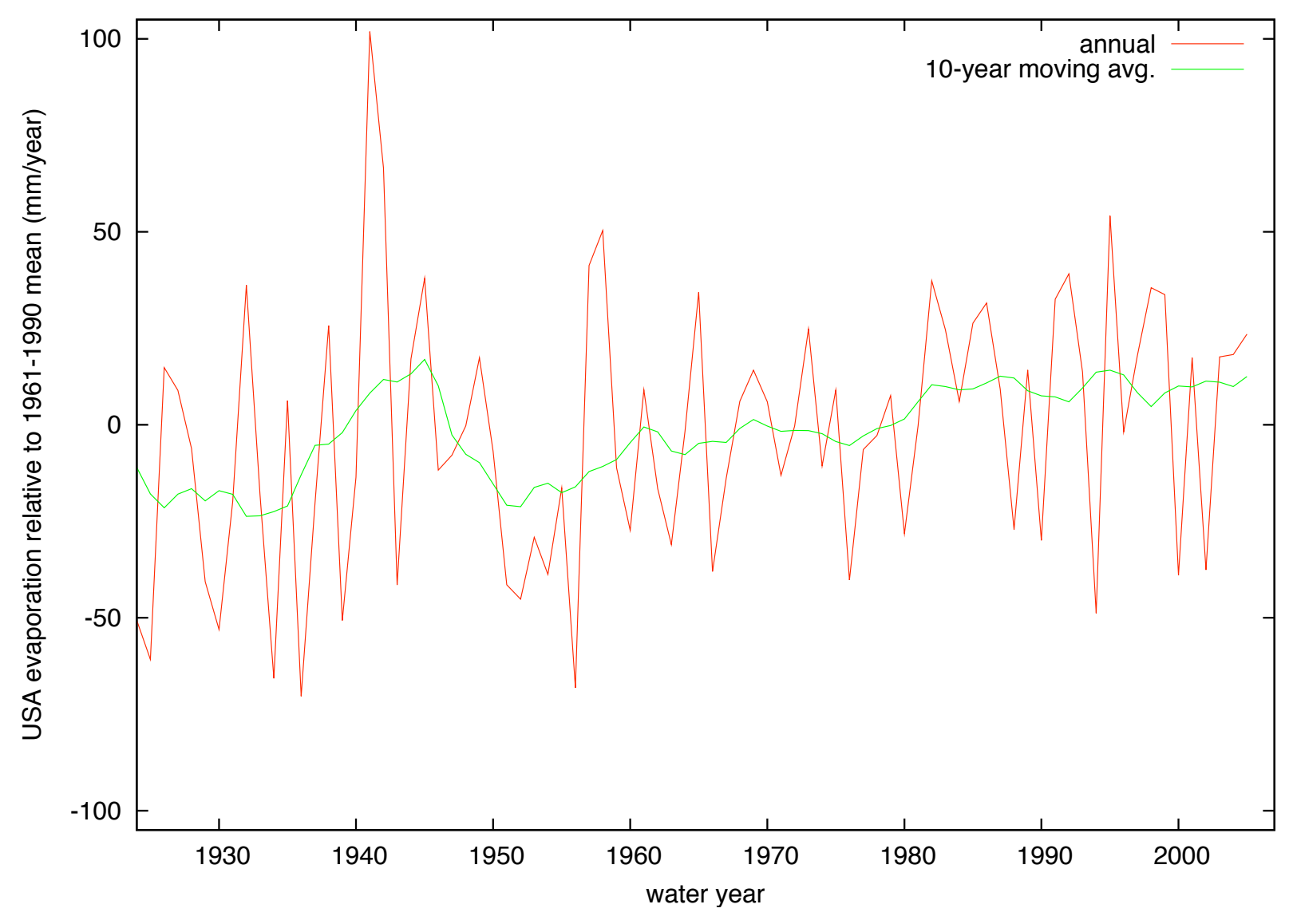

Figure 6. Yearly evaporation over the USA estimated by subtracting streamflow from precipitation. Evaporation tends to increase with hemispheric temperature taken from Jones et al. 2006, with a regression coefficient of 18.4±8.6 mm/year per K.

Conclusions

We find no consistent increase in USA streamflow with warming. Similar analyses of streamflow trends should be conducted in other countries that have adequate measurements to see if our results hold up across midlatitude land areas. However, our findings are consistent with modeling and observational work 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). Given that precipitation and streamflow have not increased thus far with warming, hot, dry conditions over the USA look increasingly likely for this century.

Acknowledgment

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