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Mapping and attribution of change in streamflow in the coterminous United States

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Abstract. An increasing trend in global streamflow has been variously attributed to global warming, land use, and a reduction in plant transpiration under higher CO_2 levels. To separate these influences for the coterminous United States, we use a set of over 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. We find that changing precipitation, which is not clearly correlated with greenhouse gas concentrations or global warming, explains most of the interannual and longer term variability in streamflow. While streamflow has indeed increased since 1920, this increase has not been steady but rather concentrated in the late 1960s, 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 from lower transpiration due to the physiological plant response to CO_2, but that this positive response is offset by concomitant increasing evaporation due to global warming. The net impact of the opposing climate and physiological effects of CO_2 emissions for streamflow is close to zero for the coterminous United States taken as a whole, but shows regional variation. Streamflow at a given amount of annual precipitation has decreased in the Pacific west, where most precipitation occurs in winter. Suppression of plant transpiration through higher CO_2 levels may be particularly important for sustaining high streamflow in recent decades in the Great Plains, where precipitation is concentrated during the growing season.

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1 Introduction

Streamflow is important both in its own right, as sustaining aquatic life and human water uses, and as a major component of the terrestrial water budget. Not surprisingly, several attempts have been made to look in streamflow records for the impact of global warming, other types of climate variability, and nonclimatic human disturbance, often with an eye to testing models used to predict future changes in the water cycle. Probst and Tardy (1987, 1989) examine discharge records of 50 large rivers, filling in gaps in the records through linear correlation with measured precipitation. They find increasing streamflow over 1910–1975 in Africa and the Americas, decreasing streamflow in Europe and Asia, and worldwide a linear trend corresponding to a 3% increase over that period, which they correlate with warming. Labat et al. (2004) analyze runoff records for 221 large rivers, estimating missing values using wavelet transforms. For the periods 1900–1975 (corresponding to Probst and Tardy's end year) and 1925–1994, they find increasing streamflow in Africa, the Americas, and Asia and decreasing streamflow only in Europe, for a global increase of 3% over 1900–1975 and 8% over 1925–1994, which they propose is evidence for acceleration of the hydrologic cycle caused by global warming; linear regression of runoff on annual global temperature gives a 4% increase per K warming.

Although Labat et al.'s claim that warming has led to globally increasing streamflow has been challenged on statistical grounds and for failing to account for the impact of land use change on streamflow (Legates et al., 2005), modeling groups have used Labat et al.'s work as a starting point to investigate what processes could be causing streamflow to increase. Gedney et al. (2006) use a land surface model driven by observed climate in an attempt to determine the causes for the increased streamflow seen by Labat et al. (2004). They find that observed climate changes are insufficient to explain the streamflow increase, while changes in land use are

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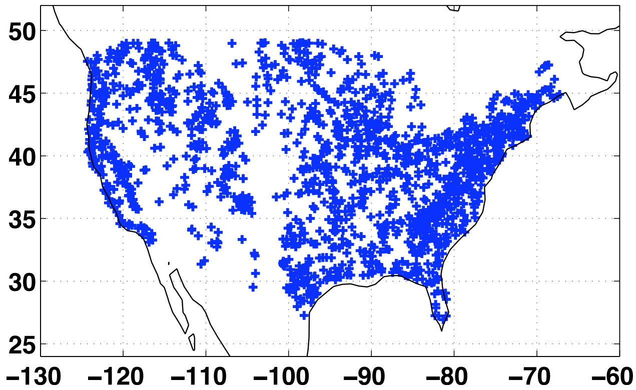

Fig. 1. Locations of HCDN stream gauges.

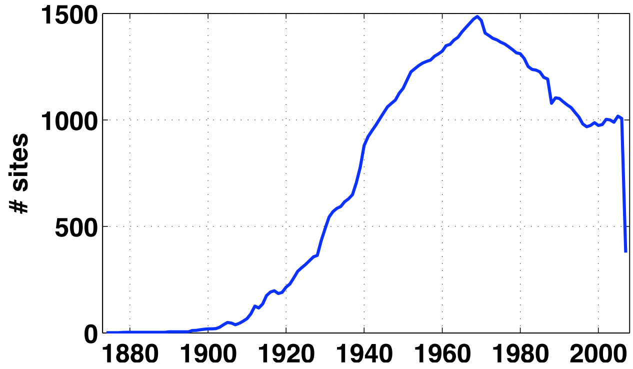

Fig. 2. HCDN sites with complete discharge records per water year. (The drop for the most recent water year, 2007, is because USGS hasn't yet estimated flows over icy periods.)

modeled to have negligible impact on continental or global streamflow. The observed trend can be matched only by including the effect of higher CO_2 levels in suppressing plant transpiration and thus increasing the share of precipitation that runs off rather than evaporates. Extending this effect into the future, Betts et al. (2007) find that including the favorable impact of high CO_2 on streamflow increases projected global streamflow by an amount comparable to that expected from the climate-induced increase in precipitation. By contrast, Piao et al. (2007), simulating 20th century trends in runoff using a different land surface model, find that suppression of transpiration is not necessary to explain the increase found by Labat et al.; in their model, transpiration is not reduced by high CO_2 levels because the increased water use efficiency is offset by faster plant growth and more leaf area. Instead, they find that land use change, specifically deforestation, can explain much of the observed increase in runoff.

Several studies have examined trends in streamflow in the United States (US), using observations from parts of the extensive United States Geological Survey (USGS) stream gauge network, usually streams from the Hydro-Climatic Data Network (HCDN), a subset of USGS stream gauges chosen for their long continuous records and minimal disturbance of flow due to human land disturbance or water diversions over their periods of record (Slack and Landwehr, 1992). Lettenmaier et al. (1994) examine trends in monthly streamflow, as well as temperature and precipitation, for 1948–1988, finding large increases in cold-season streamflow in the Northeast and Midwest over that period. Lins and Slack (1999) focus on streams with multidecade records that extend through 1993 and find that many streams have shown significantly larger low and medium flows, while high flows do not increase as much. McCabe and Wolock (2002), focusing on the period 1941–1999, find the same pattern of increasing minimum and median annual flow, but point out that the increase took place abruptly around 1970, coincident with an increase in recorded precipitation, and that therefore the increasing trend cannot be confidently extrapolated into the future. Douglas et al. (2000) analyze whether trends in high and low flows in HCDN stream gauges are significant given the spatial correlation of variability in streamflow, concluding that low flows in the Midwest have become significantly greater.

In the work presented here, our aims were (1) to use available streamflow observations to map annual streamflow departures for the coterminous US for as long a period as possible; (2) to evaluate trends in annual streamflow over the coterminous US; and (3) to correlate deduced changes in streamflow with climate variables and with CO_2 concentrations. To exclude the effects of land use change on streamflow, which may be a significant contributor to recent trends according to Piao et al. (2007), we employ only records from HCDN stations, which primarily represent drainage from minimally disturbed small watersheds.

2 Methods

2.1 Estimation of gridded streamflow

As constructed by Slack and Landwehr (1992), HCDN contains 1659 stream gauges, of which 1571 are in the coterminous United States (distribution shown in Fig. 1) and the remainder in Alaska, Hawai'i, Puerto Rico, and the Virgin Islands. Slack and Landwehr (1992) provide the available annual streamflows from HCDN gauges for the 1874–1988 water years, which we updated from USGS through 2007. (In this paper, annual streamflow, and values of associated meteorological variables such as precipitation and temperature, will be computed for water years. USGS defines a water year as extending from October of the previous calendar year through September of the current year.) The average station has 55 years with complete daily streamflow records (for which average annual streamflow can therefore be calculated), with fewer station records available before the 1940s (Fig. 2).

Most of the streams in HCDN drain small watersheds (median drainage area: 740 square km; 10th–90th percentiles: 73–6800 square km). For interpolating measured annual streamflows onto a 1° grid (1×10^4 square km cell area) covering the coterminous United States (8×10^6 square km), we therefore treated the HCDN streamflow records as point measurements of streamflow per unit watershed area. To make mapped streamflow for different years as closely comparable as possible given that different site records were available for different time periods, we began by filling in missing years in the streamflow records from the sites that were available for a given year by regularized multiple linear regression (Schneider, 2001). This approach provides estimates of the uncertainty of the filled-in missing values, as well as estimates of the mean and covariance of the streamflow records that account for the bias likely to be introduced by missing values. The streamflow records were then normalized by subtracting the long-term mean from each series and dividing by its interannual standard deviation. We chose to map these normalized streamflow departures rather than absolute streamflow per unit drainage area because the normalized departures are much less variable over small scales, particularly in mountainous terrain where absolute amounts of precipitation and streamflow can vary drastically depending on elevation and aspect. We fit a two-parameter spatial covariance model (Handcock and Stein, 1993) to the normalized streamflow series using a restricted maximum likelihood approach (Kitanidis, 1995). The correlation length of streamflow anomalies was found to be about 720 km (*e*-folding decay length; Fig. 3) and correlation decayed exponentially with distance, similar to other analyses of the spatial correlation of streamflow (Lettenmaier et al., 1994). (For simplicity, we approximated the spatial correlation as homogenous and isotropic. This is not exactly the case; for example, correlelogram analysis showed that the correlation length was about 50% greater in the east than in the more mountainous west and about 40% greater in the east-west compared with the north-south direction.) Each stream record was assigned an error which includes the estimated uncertainty in the series mean and standard deviation; the estimated uncertainty of the filled-in values; and an error term, assumed constant across records, that was intended to represent measurement error and sub-gridscale flow variability and whose magnitude (0.06 standard deviations) was determined by restricted maximum likelihood. Finally, given the spatial covariance and error structure, each year's normalized streamflow at the gauge locations was interpolated, using a standard geostatistical method (ordinary kriging) (Cressie, 1993), to a 1° grid covering the coterminous United States. Because we mapped normalized streamflow departures rather than absolute amounts, we scaled the gridded normalized streamflows by the gridded mean and interannual standard deviation of streamflow per unit area from the UNH/GRDC analysis (Fekete et al., 2002) to produce estimates of actual streamflow per unit area (in mm/year) for each water year.

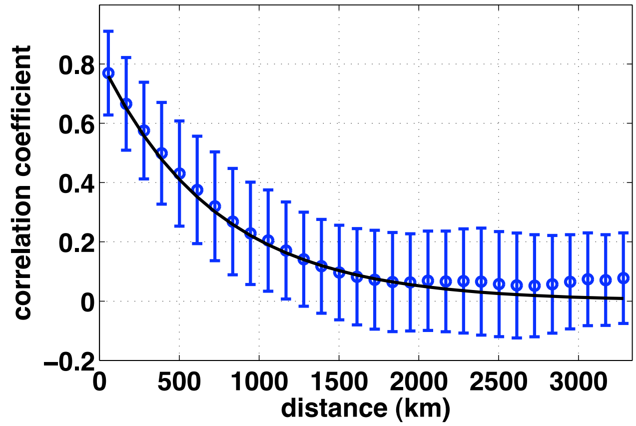

Fig. 3. Average inter-gauge correlation of annual streamflow as a function of distance between stream gauges, shown in 110-km bins. Error bars show the standard deviation of the correlation coefficient within each bin. The curve is an exponential-decay fit with a scale length of 720 km.

2.2 Climate and greenhouse-gas concentration data

We sought to correlate streamflow anomalies to anomalies in local precipitation, atmospheric CO_2 concentration, and global temperature. We used gridded precipitation from the Global Historical Climatology Network (GHCN) Version 2, which is based on quality-controlled station observations over land processed with the objective of providing the best representation of long-term variability (Peterson and Vose, 1997, http://www.ncdc.noaa.gov/oa/climate/research/ghcn/ghcngrid.html). To get more accurate ratios of streamflow to precipitation, we downscaled the precipitation amounts from the 5° resolution of GHCN to the 1° resolution of our grid using climatological gridded precipitation from the University of East Anglia's Climate Research Unit (CRU; New et al., 1999, http://www.cru.uea.ac.uk/cru/data/hrg/cru_ts_2.10/), multiplying the GHCN time series for each grid cell by a scalar representing the ratio in the CRU climatology between the precipitation at 1° resolution and that at 5° resolution. Atmospheric CO_2 concentrations were estimated from direct measurements at Mauna Loa since the late 1950s and from ice core measurements beforehand (Enting et al., 1994). Global monthly temperature anomalies were taken from CRU (Jones and Moberg, 2003, http://cdiac.esd.ornl.gov/trends/temp/jonescru/jones.html).

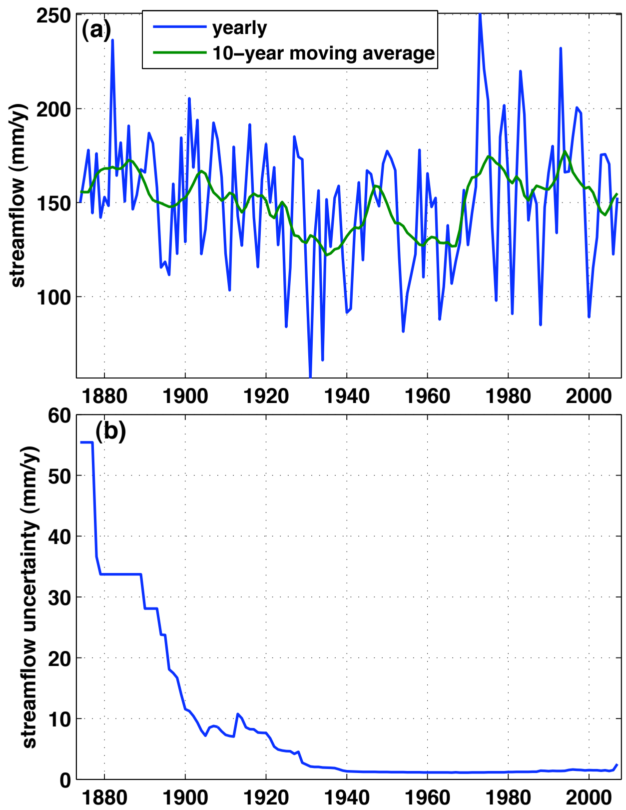

Fig. 4. (a) Estimated yearly streamflow for the coterminous United States, along with a 10-year moving average. **(b)** Uncertainty of the estimated yearly streamflow.

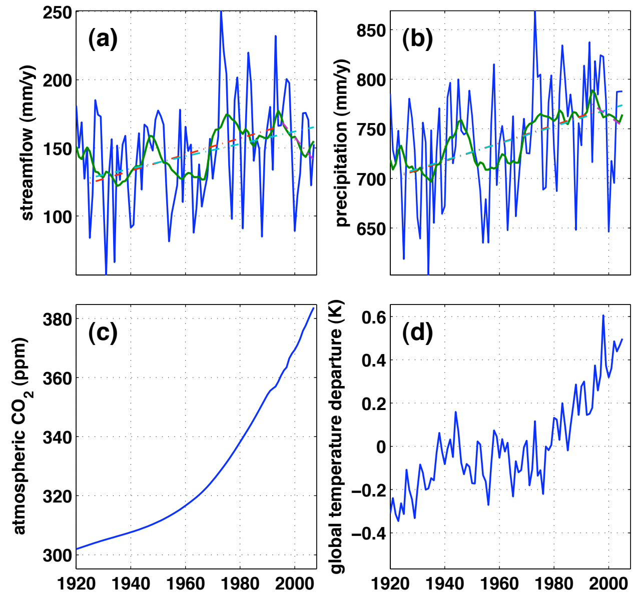

Fig. 5. (a) Estimated yearly streamflow for the coterminous United States since 1920, with a 10-year moving average (solid green line) and least-squares trendlines for 1925–1994, 1925–2007, and 1994–2007 (red, cyan and purple dashed lines, respectively). **(b)** Yearly precipitation for the coterminous United States since 1920 with a 10-year moving average and least-squares trendlines as in a. **(c)** Atmospheric CO_2 concentration. **(d)** Global surface temperature relative to the 1961–1990 mean.

3 Results

3.1 Streamflow trends and their correlation with precipitation

Figure 4 shows estimated annual streamflows for the coterminous United States, along with their uncertainty as estimated from the covariance and error structures of the HCDN records. This uncertainty was large in the first few decades, because there weren't enough records to accurately delineate patterns in annual streamflows (Fig. 2). We restricted our analysis of trends in streamflow to the period since 1920, when the streamflow gauge network appears to be dense enough to allow for accurate year-by-year reconstruction of large-scale streamflow patterns. (The estimated uncertainty shown in Fig. 4b does not include the uncertainty introduced by scaling with the the analyzed mean and standard deviation from Fekete et al. (2002). This source of uncertainty, while difficult to quantify, would be expected to affect primarily our estimate of the absolute amount of streamflow and not its interannual variability.) We found periods of low streamflow in the 1930s and 1950s–1960s, and high streamflow in the 1970s and 1980s. A linear least-squares trendline of estimated streamflows over 1925–1994 supports Labat et al.'s (2004) finding of increasing streamflow in North America over this period: the regression coefficient is $+0.57\pm0.22$ mm/year per year (p=0.03 for the null hypothesis of a regression coefficient of zero, using the F test with the number of degrees of freedom adjusted for series autocorrelation; Bretherton et al., 1999). However, the increase over this period mostly took place abruptly around 1970 (as evidenced by the 10-year moving average in Fig. 5a), rather than continuing steadily through recent decades. In fact, over the period 1994–2007, i.e. subsequent to that covered in Labat et al.'s analysis, streamflow shows a nonsignificant decreasing trend of -2.3 ± 2.2 mm/year per year (p=0.48) (Fig. 5a), whereas if the streamflow increase was closely linked to warming, as theorized by Labat et al. (2004), or to atmospheric CO_2 as suggested by Gedney et al. (2006), continuing increases would have been expected after 1970.

As recognized by McCabe and Wolock (2002) for minimum and median annual streamflows, long-term trends in mean streamflow were well correlated with trends in precipitation, which also shows an abrupt increase around 1970 followed by essentially no trend since then (Fig. 5b). High-frequency interannual fluctuation in precipitation was also

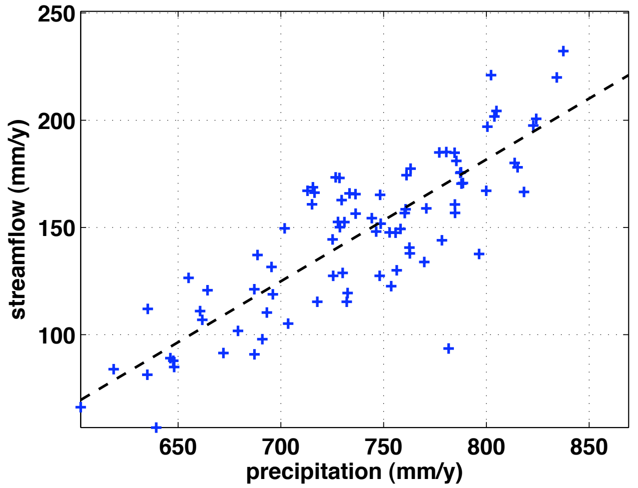

Fig. 6. Yearly coterminous United States streamflow ploted against precipitation, 1920–2005. The linear regression trendline is also drawn: streamflow=(0.54±0.04)×precipitation −(248±28) mm/year.

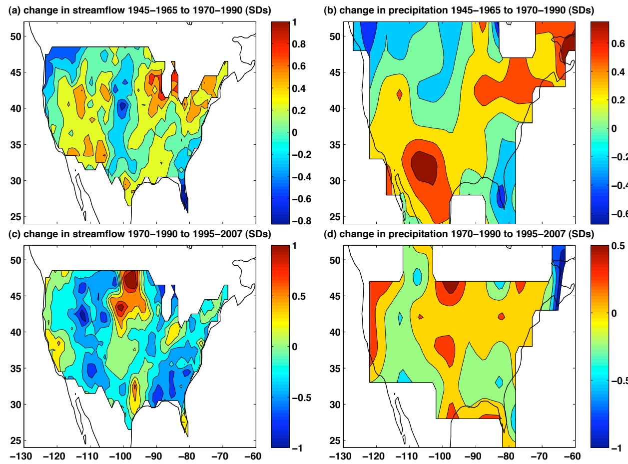

Fig. 7. (a–b) Change in average streamflow and precipitation between 1945–1965 and 1970–1990 (later period minus earlier period). **(c–d)** Same, but between 1970–1990 and 1995–2007 (1995–2005 for precipitation). Changes have been normalized by the interannual standard deviation at each point so that changes in moist and arid regions have comparable magnitude.

matched by fluctuations in streamflow. In fact, as Fig. 6 shows, most of the streamflow variability could be explained by a linear dependence on current-year precipitation (R^2=0.70).

Our gridded streamflow product permits us to compare not only trends in streamflow and precipitation averaged over the coterminous US but also spatial patterns in streamflow with spatial patterns in precipitation at comparable effective resolution over particular time periods. As an example, Fig. 7 shows maps of interdecadal change in streamflow and precipitation. Between 1945–1965 and 1970–1990, precipitation increased over most of the US, with a particularly pronounced increase in the northeast, but decreased over Florida and the northwest. Between 1970–1990 and 1995–2007 precipitation increased in the upper Great Plains and northern California but decreased in the Rocky Mountain region and in the southeast. In both cases, streamflow shows quite similar trends. Another way of showing the relationship between precipitation and streamflow is to map the local correlation between the two (Fig. 8). The quantitative relationship between precipitation and streamflow change shows that precipitation mostly goes into streamflow in the moist east (regression coefficient near 1 in Fig. 8a) and mostly evaporates in the arid west (regression coefficient near 0). The fraction of interannual variance in streamflow explained by variability in precipitation, as given by the regression correlation coefficient (Fig. 8b), is high (close to or above 0.5) for most of the coterminous US, but relatively low for the Great Plains in the center.

Comparing the regression coefficient of precipitation on streamflow (Fig. 8) with the fraction of climatological precipitation that falls during the warmest six months of the year (Fig. 9a), we see that the fraction of interannual variability of streamflow that can be explained by precipitation fluctuations was smallest in the Great Plains, where summer precipitation dominates (so that the timing of rainfall and the antecedent soil moisture status may be relatively more important to determining streamflow than the annual total precipitation amount), and strongest in the moist east and the Pacific coast (Fig. 8b; Table 1). Also, in areas that get mostly summer precipitation a greater fraction of precipitation evaporates than in areas where winter precipitation dominates (Table 1).

3.2 Impact of global warming and atmospheric CO_2 on streamflow

While the major direct cause of interannual variability in streamflow is variability in precipitation, changing temperature and CO_2 level might also be expected to affect streamflow, the former through influencing evaporation rates, and the latter by affecting plant water use efficiency. One difference between the two kinds of impact is their seasonality: while higher temperature at any time of year accelerates evaporation (though this impact might be greater in the warmer months when vapor pressure deficits are greatest), higher plant water use efficiency would reduce transpiration only during the growing season, which typically (for the coterminous US) corresponds to the warm months.

Since (greenhouse) warming and rising CO_2 have been well correlated and are likely to remain so in coming decades, we first examined the net effect of the combination of the physiological impact of high CO_2 on plant

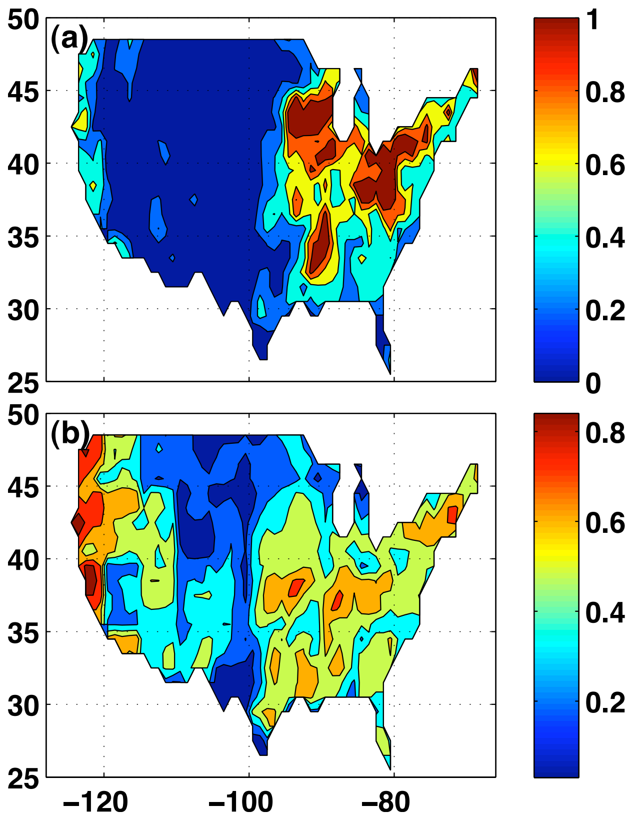

Fig. 8. (a) Regression coefficient on precipitation of annual streamflow, 1920–2005 (dimensionless, mm/year per mm/year). **(b)** Fraction of interannual variability in streamflow explainable by linear regression on annual precipitation (R^2).

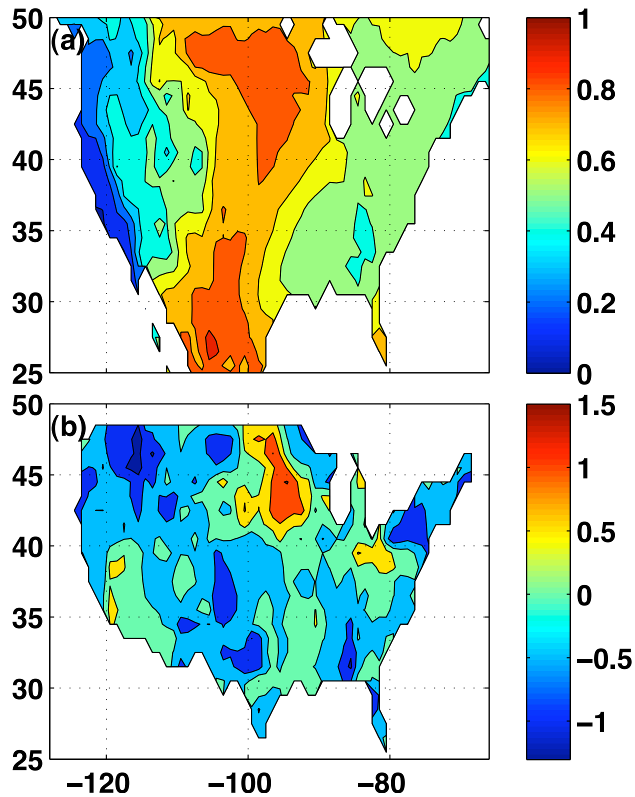

Fig. 9. (a) Summer dominance of precipitation, defined as the fraction of climatological annual precipitation that falls during warmer than average months of the year. **(b)** Apparent response of streamflow to greenhouse warming: the regression coefficient of atmospheric CO_2 level on annual streamflow in a multiple regression of streamflow against precipitation and (rising) CO_2 level. 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, so that the regression coefficients shown in red and dark blue are significantly different from zero at the 95% level.

transpiration and the impact on evaporation of warming induced by greenhouse gas emissions. Regression of streamflow against precipitation and CO_2 showed that the overall effect of greenhouse warming, holding precipitation constant, on streamflow is not significant for the coterminous US as a whole, with a regression coefficient of -3 ± 12 mm/year streamflow change per 100 ppm increase in atmospheric CO_2 (100 ppm is equal to the increase in CO_2 concentration from preindustrial times to the decade of the 2000s) (Table 1).

In an attempt to isolate the impact on streamflow of global warming and of increasing ambient CO_2 levels, we performed multiple linear regression of streamflow against annual precipitation, CO_2 level, and temperature. The strong correlation of large-scale temperature with CO_2 levels increases uncertainties when attempting to distinguish the separate effects of these two factors using linear regression. For the coterminous US we found opposing impacts of temperature and CO_2 in the expected directions, with warming reducing streamflow significantly while higher CO_2 nonsignificantly increases streamflow (Table 1).

While rising greenhouse gas concentrations have had no net impact on streamflow for the coterminous US as a whole, there are significantly different regional responses depending on precipitation seasonality (Fig. 9; Table 1). Areas where most precipitation falls in the cold season (the Pacific west, whose climate has Mediterranean features) showed a greater and significant reduction in streamflow (-27 ± 11 mm/year streamflow change per 100 ppm increase in atmospheric CO_2) after adjusting for precipitation change, while areas where summer rain is dominant (the Great Plains) show nonsignificant increases in streamflow ($+17\pm11$ mm/year streamflow change per 100 ppm increase in atmospheric CO_2; Table 1). Regression of regional streamflow against annual precipitation, CO_2 level, and temperature shows significant reductions in streamflow in response to global warming in regions of winter-dominant and evenly distributed

Table 1. Streamflow variability for the coterminous US and for regions grouped by precipitation seasonality.

	Entire coterminous US	Fraction of precipitation in warm season <35%	35–65%	>65%
Area (10^6 km^2)	7.85	0.68	3.93	3.19
Mean precipitation (mm/year)	736	748	837	599
Mean streamflow (mm/year)	151	311	211	39
Regression of streamflow against precipitation				
Regression R^2	0.70	0.88	0.82	0.55
Streamflow: precipitation regression coefficient[a]	0.54±0.04**	0.49±0.02**	0.69±0.04**	0.31±0.03**
Intercept (mm/year)[b]	463	126	542	475
Regression of streamflow against precipitation and pCO$_2$				
Regression R^2	0.70	0.89	0.82	0.57
Streamflow: CO_2 regression coefficient[c]	−3±12	−27±11*	−10±13	+17±11
Regression of streamflow against precipitation, pCO$_2$, and temperature				
Regression R^2	0.72	0.90	0.83	0.57
Streamflow: CO_2 regression coefficient	+37±21	+20±21	+42±24	+32±20
Streamflow:temperature regression coefficient[d]	−52±22*	−59±22**	−66±26*	−19±21

* Correlation (adjusted for series autocorrelation) is significant at the 0.05 level
** Significant at the 0.01 level
[a] mm/year streamflow per mm/year precipitation
[b] Precipitation at zero streamflow ("baseline" level of evaporation and plant transpiration)
[c] mm/year streamflow per 100 ppm CO_2
[d] mm/year streamflow per K

precipitation, while CO_2 level showed a nonsignificant positive correlation with streamflow in all three regions (Table 1).

For the regression analyses involving temperature just described and shown in the bottom rows of Table 1, we used global temperature as a predictor variable in order to quantify the impact of global warming on streamflow adjusted for precipitation and CO_2 change. Similar regressions using Northern Hemisphere (CRU) or local (GHCN) temperature series instead of global temperature give qualitatively similar results (not shown), with a negative correlation of streamflow with temperature alongside a (usually nonsignificant) positive correlation of streamflow with CO_2 level.

4 Discussion

4.1 Is greenhouse warming increasing streamflow?

Figure 10a shows coterminous United States precipitation versus global temperature for each year in 1901–2005. While the two time series show a nominally significant positive correlation of +0.35 ($p<0.001$) because the higher precipitation after 1970 corresponds to warmer global temperatures, segmenting the time series at 1970 shows that the correlation is mostly due to the abrupt jump in precipitation around 1970 rather than a more consistent trend (correlation for 1901–1970 +0.19, for 1970–2005 +0.09, both with $p>0.05$). This jump in precipitation has been tentatively linked with changing circulation patterns in the Atlantic Ocean, possibly reinforced by increasing aerosol emissions in the 1960s (Baines and Folland, 2007). Thus, there is no clear response of coterminous United States precipitation to global temperature in the observational record. Coterminous United States streamflow similarly jumps round 1970, with no significant response to global temperature when the time series is segmented (Fig. 10b).

Absent a direct effect of greenhouse warming on coterminous US precipitation, parts of the US, specifically those where most precipitation falls in the cold season, show a significant negative impact of higher greenhouse-gas levels on streamflow, which could be explained through the increased evaporation due to global warming more than offsetting the

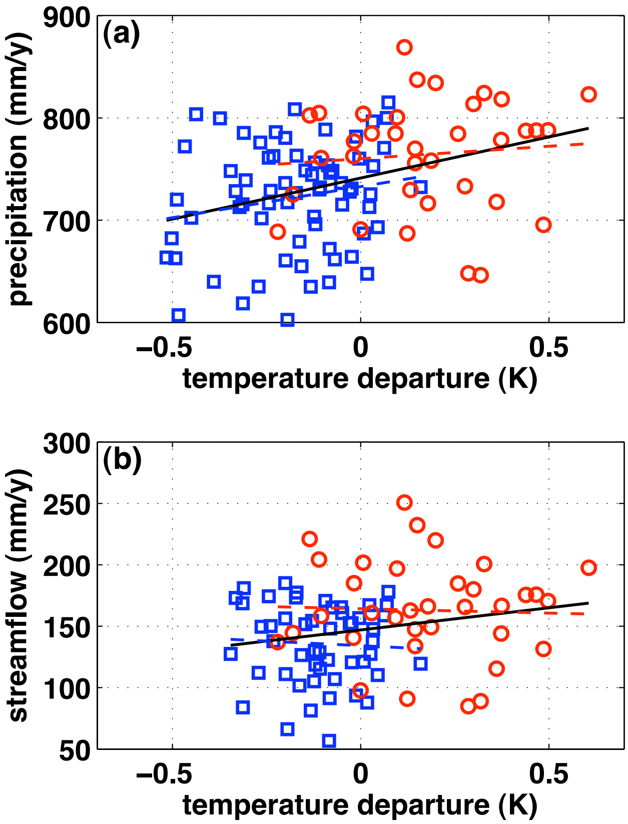

Fig. 10. (a) Annual global temperature and coterminous US precipitation, 1901–2005. Blue squares are years from 1901–1970, red circles are years from 1971–2005. The solid line is the least-squares regression line for the entire period, while the blue and red dashed lines are regression lines for the periods 1901–1970 and 1970–2005 respectively. While over the whole period precipitation is significantly positively correlated with temperature (R^2=0.12), the correlation is weaker and not significant for the two subperiods. **(b)** Annual global temperature and coterminous US streamflow, 1920–2005. Blue squares are years from 1920–1970, 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 1920–1970 and 1970–2005 respectively. Here the correlation for the entire period is weak (R^2=0.04) and not significant, and is negative (also nonsignificant) for the two subperiods.

increased plant water use efficiency due to higher CO_2 concentrations. Our inference that total evaporation, including plant transpiration, is stable or increasing with warming is consistent with in situ measurements of evaporation using weighing lysimeters (Golubev et al., 2001).

We found that the positive CO_2 impact on streamflow is strongest compared to the negative temperature impact in parts of the United States where summer precipitation dominates. This pattern agrees with the expectation that the impact of increased plant water use efficiency on streamflow should be relatively largest where precipitation is concentrated during the growing season and therefore is used by plants rather than running off and contributing to streamflow, as opposed to where most precipitation occurs in winter so that growing-season transpiration has a relatively smaller impact on streamflow (Wigley et al., 1984). By contrast, abiotic evaporation increases with temperature regardless of season or CO_2 level.

4.2 What do observed trends suggest about future moisture regimes?

Our results show that fitting a linear trend to streamflow data can be highly misleading for understanding decadal variability and for extending observed patterns into the future. While coterminous United States streamflow and precipitation have indeed increased in recent decades, this increase took place abruptly over a few years around 1970, rather than as part of a steady "acceleration of the hydrologic cycle" in step with greenhouse gas concentrations or global warming. Thus, at least for the US there is no clear reason to expect continued increases in streamflow with greater warming. If precipitation follows its post-1970 trend and fails to increase strongly with additional warming, streamflow would likely continue to decrease, as it has since the early 1990s, over at least some parts of the US due to increased evaporative demand incompletely offset by the physiological impact of CO_2 on plant transpiration. Indeed, increasing drought over the United States since the early 1990s is proposed to have caused a reduction in the summer drawdown of atmospheric CO_2 observed at Mauna Loa, as water stress reduced plant carbon uptake during the growing season (Buermann et al., 2007). The global trend since the 1970s has also been toward more frequent drought occurrence (Dai et al., 2004). Extending our work through mapping streamflow trends in other land areas where many long records are available would help give a clearer picture of how decadal hydrologic variability and the effects of greenhouse warming on the water cycle vary between continents and biomes.

Considering only annual mean streamflow and precipitation may not be sufficient for understanding past and future changes in water stress and water resource availability. For example, part of the increase in streamflow observed in the Great Plains that our regression analysis attributed to increasing atmospheric CO_2 could instead be due to reduced interannual precipitation variability (Garbrecht and Rossel, 2002) or to a disproportionate increase in cold-season (as compared with summer) precipitation (Garbrecht et al., 2004). Our interpolation technique could equally well be applied to seasonal or monthly as well as annual mean streamflow, and thus distinguish the hydrologic impacts of these as well as other seasonally specific factors such as advances in spring snowmelt and changing vegetation phenology. Changes in precipitation intensity (Groisman et al., 2001) as well as precipitation amount might also affect streamflow and other aspects of the water cycle. Comparing trends in gridded streamflow from a larger gauge network with the trend estimated using HCDN offers one way to validate model assessments of the impact on streamflow of human land use and water diversion, whereas in this study we chose to obtain trend estimates that exclude land use impacts insofar as possible. Finally, combining gridded streamflow and precipitation with remotely sensed water storage would give a fuller picture of how climate variability is affecting stored soil water and groundwater.

5 Conclusions

We developed maps of annual streamflow anomalies over the coterminous United States using streamflow records selected to reflect minimum direct impacts from human land disturbance and water diversion. We find that streamflow increased around 1970 in concert with an increase in precipitation, but has not increased since then. Our analysis supports net drying in some regions, and no change in others, as a result of greenhouse warming, with tentative evidence for the opposing effects of warming and CO_2 increase. Depending on how this interplay between temperature and direct CO_2 effect of greenhouse gas emissions evolves, there is a high risk of reduced water supplies and increased plant water stress with continued warming in coming decades.

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References

Baines, P. G. and Folland, C. G.: Evidence for a rapid global climate shift across the late 1960s, J. Climate, 20, 2721–2744, doi:10.1175/JCLI4177.1, 2007.

Betts, R., Boucher, O., Collins, M., Cox, P., Falloon, P., Gedney, N., Hemming, D., Huntingford, C., Jones, C., Sexton, D., et al.: Projected increase in continental runoff due to plant responses to increasing carbon dioxide., Nature, 448, 1037–41, 2007.

Bretherton, C. S., Widmann, M., Dymnikov, V. P., Wallace, J. M., and Bladé, I.: The effective number of spatial degrees of freedom of a time-varying field, J. Climate, 12, 1990–2009, 1999.

Buermann, W., Lintner, B. R., Koven, C. D., Angert, A., and Pinzon, J. E.: The changing carbon cycle at Mauna Loa Observatory, Proceedings of the National Academy of Sciences, 104, 4249–4254, 2007.

Cressie, N. A.: Statistics for Spatial Data, Wiley, revised edn., 1993.

Dai, A., Trenberth, K. E., and Qian, T.: A global data set of Palmer Drought Severity Index for 1870-2002: Relationship with soil moisture and effects of surface warming, J. Hydrometeorol., 5, 1117–1130, 2004.

Douglas, E. M., Vogel, R. M., and Kroll, C. N.: Trends in floods and low flows in the United States: impact of spatial correlation, Journal of Hydrology, 240, 90–105, http://www.sciencedirect.com/science/article/B6V6C-41T1F8V-6/1/f1fa3af54563a94311ab29cbf2b9bbc9, 2000.

Enting, I., Wigley, T. M. L., and Heimann, M.: Future Emissions and Concentrations of Carbon Dioxide: Ocean/Atmosphere/Land Analyses, Technical Paper no. 31, CSIRO Division of Atmospheric Research, 1994.

Fekete, B. M., Vörösmarty, C. J., and Grabs, W.: High resolution fields of global runoff combining observed river discharge and simulated water balances, Global Biogeochem. Cycles, 16, 1042, doi:10.1029/1999GB001254, 2002.

Garbrecht, J., Liew, M. V., and Brown, G. O.: Trends in precipitation, streamflow, and evapotranspiration in the Great Plains of the United States, Journal of Hydrologic Engineering, 9, 360–367, doi:10.1061/(ASCE)1084-0699(2004)9:5(360), 2004.

Garbrecht, J. D. and Rossel, F. E.: Decade-scale precipitation increase in Great Plains at end of 20th century, Journal of Hydrologic Engineering, 7, 64–75, doi:10.1061/(ASCE)1084-0699(2002)7:1(64), 2002.

Gedney, N., Cox, P. M., Betts, R. A., Boucher, O., Huntingford, C., and Stott, P. A.: Detection of a direct carbon dioxide effect in continental river runoff records, Nature, 439, 835–838, doi:10.1038/nature04504, 2006.

Golubev, V., Groisman, P., Speranskaya, N., Zhuravin, S., Menne, M., Peterson, T., and Malone, R.: Evaporation changes over the contiguous United States and the former USSR: A reassessment, Geophysical Research Letters, 28, 2665–2668, 2001.

Groisman, P. Y., Knight, R. W., and Karl, T. R.: Heavy precipitation and high streamflow in the contiguous United States: Trends in the twentieth century, B. Am. Meteor. Soc., 82, 219–246, 2001.

Handcock, M. S. and Stein, M. L.: A Bayesian analysis of kriging, Technometrics, 35, 403–410, 1993.

Jones, P. D. and Moberg, A.: Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001, J. Climate, 16, 206–223, 2003.

Kitanidis, P. K.: Quasi-linear geostatistical theory for inversing, Water Resources Research, 31, 2411–2420, 1995.

Labat, D., Godderis, Y., Probst, J. L., and Guyot, J. L.: Evidence for global runoff increase related to climate warming, Advances in Water Resources, 27, 631–642, 2004.

Legates, D., Lins, H., and McCabe, G.: Comments on "Evidence for global runoff increase related to climate warming" by Labat et al., Advances in Water Resources, 28, 1310–1315, 2005.

Lettenmaier, D. P., Wood, E. F., and Wallis, J. R.: Hydro-climatological trends in the continental United States, 1948-88, J. Climate, 7, 586–607, 1994.

Lins, H. F. and Slack, J. R.: Streamflow trends in the United States, Geophys. Res. Lett., 26, 227–230, doi:10.1029/1998GL900291, 1999.

McCabe, G. J. and Wolock, D. M.: A step increase in streamflow in the conterminous United States, Geophys. Res. Lett., 29, 2185, doi:10.1029/2002GL015999, 2002.

New, M., Hulme, M., and Jones, P.: Representing twentieth-century space-time climate variability. Part I: Development of a 1961–90 mean monthly terrestrial climatology, J. Climate, 12, 829–856, 1999.

Peterson, T. C. and Vose, R. S.: An overview of the Global Historical Climatology Network temperature data base, Bulletin of the American Meteorological Society, 78, 2837–2849, 1997.

Piao, S., Friedlingstein, P., Ciais, P., de Noblet-Ducoudre, N., Labat, D., and Zaehle, S.: Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends, Proceedings of the National Academy of Sciences, 104, 15 242–15 247, doi:10.1073/pnas.0707213104, 2007.

Probst, J. L. and Tardy, Y.: Long range streamflow and world continental runoff fluctuations since the beginning of this century, J. Hydrol., 94, 289–311, doi:10.1016/0022-1694(87)90057-6, 1987.

Probst, J.-L. and Tardy, Y.: Global runoff fluctuations during the last 80 years in relation to world temperature change, American Journal of Science, 289, 267–285, 1989.

Schneider, T.: Analysis of incomplete climate data: Estimation of mean values and covariance matrices and imputation of missing values, Journal of Climate, 14, 853–871, doi:10.1175/1520-0442(2001)014⟨0853:AOICDE⟩2.0.CO;2, 2001.

Slack, J. R. and Landwehr, J. M.: Hydro-Climatic Data Network (HCDN): A U.S. Geological Survey Streamflow Data Set for the United States for the Study of Climate Variations, 1874-1988, Tech. rep., USGS Open-File Report 92–129, http://pubs.usgs.gov/wri/wri934076/, 1992.

Wigley, T. M. L., Briffa, K. R., and Jones, P. D.: Atmospheric carbon dioxide: Predicting plant productivity and water resources, Nature, 312, 102–103, doi:10.1038/312102a0, 1984.