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Trends in evaporation and surface cooling in the Mississippi River basin

P. C. D. Milly, K. A. Dunne

U. S. Geological Survey and Geophysical Fluid Dynamics Laboratory/NOAA, Princeton, New Jersey

Abstract. A synthesis of available data for the Mississippi River basin (area $3x10^6$ km^2) reveals an upward trend in evaporation during recent decades, driven primarily by increases in precipitation and secondarily by human water use. A cloud-related decrease in surface net radiation appears to have accompanied the precipitation trend. Resultant evaporative and radiative cooling of the land and lower atmosphere quantitatively explains downward trends in observed pan evaporation. These cooling tendencies also reconcile the observed regional atmospheric cooling with the anticipated regional "greenhouse warming." If recent high levels of precipitation (which correlate with the North Atlantic Oscillation) are mainly caused by an internal climatic fluctuation, an eventual return to normal precipitation could reveal heretofore-unrealized warming in the basin. If, instead, they are caused by some unidentified forcing that will continue to grow in the future, then continued intensification of water cycling and suppression of warming in the basin could result.

Introduction

Climate variations, global or otherwise, are experienced by human society, to a large extent, at the regional scale; this creates a need for understanding of controls on regional climate variability. For the Mississippi River basin during 1949-1997, the linear trend over time in near-surface air temperature was negative, differing significantly from the regional warming in a climate model forced by increases in greenhouse gases and direct effects of sulfate aerosols [*Knutson et al.*, 1999]. During the same period, precipitation and runoff in the basin increased substantially [*Karl and Knight, 1998; Lins and Slack, 1999*]. The trend in evaporation, which is the crucial link between surface water and energy balances, has not been quantified; observed decreases in pan evaporation (the rate of evaporative water loss from standardized, water-filled pans) [*Peterson et al.*, 1995] can be given widely divergent interpretations and, taken alone, do not constrain even the sign of the trend in basin evaporation [*Brutsaert and Parlange*, 1998]. Therefore, we analyzed surface water and energy balances for the basin in an attempt to quantify trends in water and energy fluxes, including evaporation; to understand physical connections among the trends; and to evaluate the possible influence of water-flux trends on atmospheric temperature at regional scale.

Trends in naturalized evaporation and consumptive water use

A water-mass balance for the Mississippi basin (Figure 1) quantifies total evaporation, evaporation induced by irrigation and other human activities (consumptive water use, *U*), and their difference (naturalized evaporation, *E*) (Figure 2). Water-resource development has played only a very small role in the time-mean water balance, but the trend in *U* is not negligible

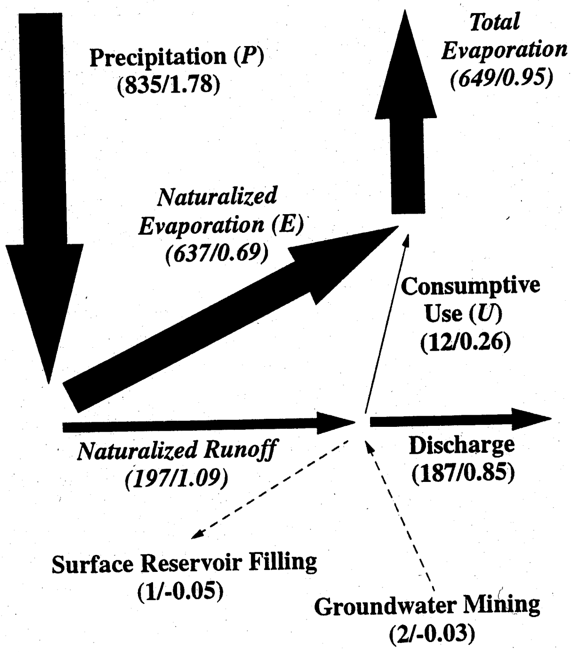

Figure 1. Balance relations among water fluxes (arrows) for the Mississippi River basin above Vicksburg, Mississippi. Parenthetic quantities are the long-term annual means (numerators, mm y^{-1}, proportional to arrow shaft width) and linear trends in annual means (denominators, mm y^{-2}), both for the period 1949-1997. Means and trends were evaluated from estimated annual time series of each flux. The precipitation time series was evaluated by spatial interpolation of monthly anomalies of point measurements at 1,012 gauges in the Global Historical Climatology Network (GHCN), with the anomalies defined as departures from at-gauge means; monthly gauge values were adjusted for gauge bias [*Legates and Willmott*, 1990]. Discharge data were provided by the U.S. Geological Survey. Storage rates associated with filling of surface reservoirs and long-term depletion of groundwater were estimated from data summaries [*Ruddy and Hitt*, 1990; *Dugan and Cox*, 1994]. Consumptive use was estimated from periodic water-use assessments (*Solley et al.*, 1998; *MacKichan*, 1951, 1957; *MacKichan and Kammerer*, 1961; *Murray*, 1968; *Murray and Reeves*, 1972, 1977; *Solley et al.*, 1983, 1988, 1993). Remaining fluxes (italics) were deduced by mass balance from the others.

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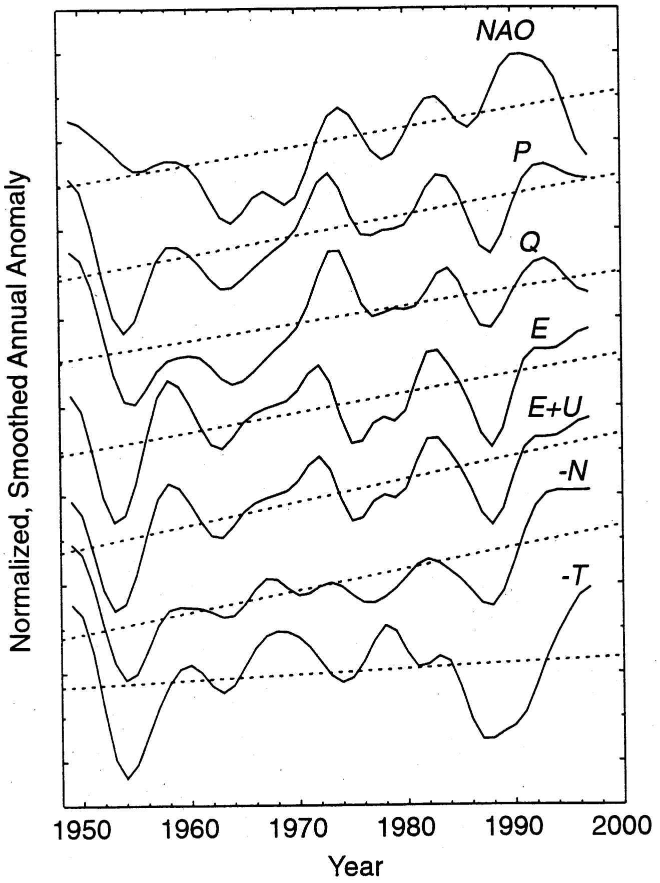

Figure 2. Normalized, smoothed anomalies, with linear trends, of North Atlantic Oscillation index [*Hurrell*, 1995] (*NAO*); annual precipitation (*P*), naturalized runoff (*Q*), naturalized evaporation (*E*), total evaporation (*E+U*), and air temperature (*T*); and warm-season (May-September) pan evaporation (*N*). Axes are inverted for *T* and *N*. Pan evaporation was interpolated from data of the National Climatic Data Center for 404 stations, and air temperature from data of the GHCN for 915 stations. All time series were first smoothed by an 11-point binomial filter and the smoothed series were then expressed as deviations from the time-mean values, normalized by standard deviations. Successive curves are offset by 2 standard deviation units. (Annual weights for the 11-point filter are 0.001, 0.010, 0.044, 0.117, 0.205, 0.246, 0.205, 0.117, 0.044, 0.010, 0.001.)

compared to the trend of natural fluxes (Figure 1); the growth in consumptive use accounts for more than a quarter of the growth in total evaporation.

Trends in water and energy supplies

The naturalized evaporation increase could be driven by the precipitation (*P*) increase and/or by increased energy availability at the surface. To quantify the relative importance of these two controls, we applied a semi-empirical water-balance theory [*Budyko*, 1974, p. 321-326], which explains the natural partitioning of precipitation into runoff and evaporation as a function of the relative magnitudes of available energy (surface net radiation, *R*) and water (*P*),

$$E / P = \phi (R / LP) , \qquad (1)$$

in which $\phi(x) = [x(\tanh x^{-1})(1 - \cosh x + \sinh x)]^{1/2}$ and *L* is the latent heat of vaporization of water. From (1) we can derive a perturbative relation among long-term linear trends (subscript *t*),

$$E_t = (\phi - \phi' R/LP)\, P_t + (\phi'/L)\, R_t , \qquad (2)$$

in which ϕ' is the derivative of ϕ. Our data for *E* and *P* imply $\phi = 0.764$, leading to $R/LP = 1.23$, and $\phi' = 0.263$. Thus, a naturalized evaporation trend of 0.78 mm y^{-2} would be induced by P_t in the absence of a radiation trend. This is greater than the estimated trend (Figure 1); the difference could be explained, according to (2), by a decreasing trend of net radiation (R_t/L = -0.37 mm y^{-2}, R_t = -0.030 W m^{-2} y^{-1}). A radiation trend of this magnitude and sign is also supported by calculations we performed using empirical relations between cloud cover and surface radiative fluxes [*Brutsaert*, 1982, p. 128-144], given estimates of sensitivity of cloud cover to precipitation for the region [*Plantico et al.*, 1990].

Trends in sensible heat flux and pan evaporation

Inferences regarding evaporation and radiation have consequences for the surface energy balance. Sensible heating of the lower atmosphere by the land surface (*H*) is approximately equal to the difference between surface radiative heating and evaporative cooling. In terms of trends,

$$H_t = R_t - L\,(E_t + U_t) . \qquad (3)$$

Our analysis implies a strong negative trend in *H* (-0.11 W m^{-2} y^{-1}) over the Mississippi basin. Long-term, areally extensive observations of energy fluxes are not available for comparison. The best available indirect measure of energy balance may be pan evaporation (*N*). Pan evaporation is linearly related to the regional energy availability, which can be equated with *R*, and to the deficit of regional evaporation below its energy-limited value [*Brutsaert and Parlange*, 1998]. The latter is equivalent to *H*, leading to (in terms of trends)

$$aN_t = R_t/L + bH_t/L , \qquad (4)$$

where we shall take values [*Brutsaert*, 1982, *Brutsaert and Parlange*, 1998] a=0.8 and b=1.1. (The complementary relation between *E* and *N*, implied by (3) and (4), is evident in the interdecadal fluctuations in Figure 2.) Using our best estimates of $E_t + U_t$ and R_t in (3) and (4), we expect a -2.3 mm y^{-2} trend of annual pan evaporation. *Peterson et al.* [1995] have noted a decreasing trend of warm-season (May-September, the period when about two thirds of annual pan evaporation occurs) pan evaporation across the United States. Our analysis of pan data reveals a warm-season trend over the Mississippi basin of -1.9 mm (warm season)$^{-1}$ y^{-1}. The trend in annual pan evaporation could be either larger or smaller than the warm-season trend, depending on the sign of the unmeasured cold-season trend. When we examine the monthly structure of the warm-season trend, we find that it is most negative during May, August, and September, and that its monthly structure follows closely that of trends in precipitation. We infer from this and from the monthly pattern of precipitation trend that the pan evaporation trend is negative also during the cold season, with an annual trend probably between -2 and -3 mm y^{-2}. The consistency of this inference with our theoretical estimate of N_t supports our inference of a negative value for R_t/L ; if we were to set the radiation trend to zero in (3) and (4), we would then obtain N_t

= -1.3 mm y^{-2}, seemingly inconsistent with the pan observations.

Effect on near-surface air-temperature trend

Two strong controls on variations in near-surface air temperature are surface heating and horizontal advection of heat; herein we focus on the former, which is internal to the basin and whose relative impact we expect to increase with spatial scale. The robust negative trend in surface heating of the atmosphere above the Mississippi basin might have influenced the near-surface temperature trend there. Our estimate of the 1949-1997 temperature trend is -0.004 K y^{-1}. To place this in the context of the expected atmospheric warming due to anthropogenic changes in radiative forcing, we analyzed results from a numerical climate-change experiment [*Knutson et al.*, 1999]. One control (constant radiative forcing) experiment and five replicate transient experiments sharing common estimates of historical changes in radiative forcing due to greenhouse gases and direct effects of sulfate aerosols, but different initial conditions, were performed using a coupled ocean-atmosphere-land model. The Mississippi-basin warming trend in the transient experiments (mean±σ, n=5) is 0.016±0.004 K y^{-1}. We suggest that the large discrepancy with observations is related to the downward trend of H in the basin. To test this hypothesis, we simultaneously regressed the observed temperature (T) against the model-estimated warming signal (T_G, Figure 3) and the observation-based surface-heating time series, obtaining

$$\delta T = 0.685\,(\delta T_G) + [0.0105\ \mathrm{K/(mm\ y^{-1})}](\delta R/L - \delta E - \delta U), \qquad (5)$$

where δ represents smoothed annual anomalies. (The temporal distribution of δR was defined as $(R_t\,/P_t)\ \delta P$, under the assumption that precipitation-related cloud-cover variations are the dominant control of R variations. The regression equation (5) explains 48% of the variance, mostly through the surface heating term.) When the historical temperature series is adjusted for the fluctuations in heat flux using the inferred sensitivity of temperature to surface heating, the trend in residual temperature is a large fraction of the model-estimated warming (Figure 3). As an independent test, we used the control experiment to determine the model sensitivity of temperature to heating, finding a value of 0.0112 K/(mm y^{-1}), in agreement with the observational estimate. These results suggest that surface heating anomalies and anthropogenic radiative forcing have both had significant, and mutually opposing, influences on temperatures in the Mississippi basin.

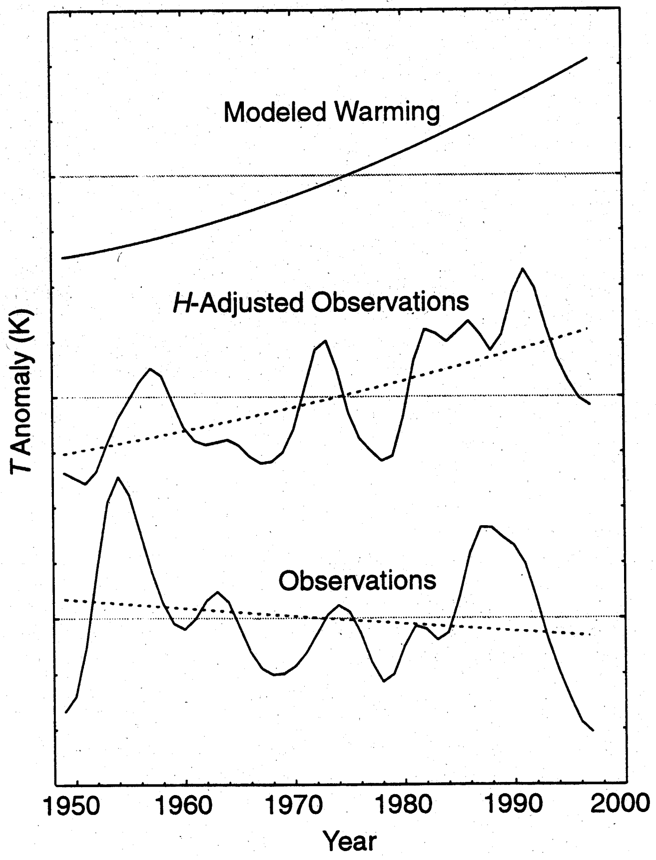

Figure 3. Observed temperature anomaly, with and without adjustment for surface heat-flux anomalies, and model-estimated warming signal, T_G. Also shown are fitted second-order polynomials for the two observation-based time series. Successive curves are offset by 1 K. The warming T_G = (0.0013 K) [max (τ -1942.2, 0) $]^{1.64}$, where τ is year number, was fitted to the five-scenario-mean model estimate of warming induced by changes in greenhouse gases and direct effects of sulfate aerosols [*Knutson et al.*, 1999].

Control of the precipitation trend

Given the apparent control of temperature (through evaporative and probably cloud-induced radiative cooling of the surface) by precipitation, the origin of the precipitation trend is of interest. The precipitation trend is a regional manifestation either of unforced (internal) variability or of a forced hydroclimatic change (or of both). We evaluated the null hypothesis (unforced variability) using two complementary approaches. The simpler method treats annual precipitation as an uncorrelated random process. Under that assumption, a trend of the observed magnitude or larger would be expected with about 5% probability. We also used the results from the climate model to place the estimated precipitation trend in the context of internal variability and anthropogenic climatic change associated with greenhouse-gas forcing and direct effects of sulfate aerosols. (In the control experiment, the mean and standard deviation of P for the Mississippi basin were 761 and 74 mm y^{-1}, indicating a slightly less intense water cycle in the model than in the observations, but with a coefficient of variation of P equal to 0.10 in both the model and the observations. The modeled index of dryness R/LP was 1.26.) The observed precipitation trend, when adjusted for the small difference between observed and modeled precipitation variance, was exceeded in about 3% of the 49-year periods in the control experiment. For the five transient experiments, the 1949-1997 trend was 0.11±0.39 mm y^{-2}; thus, the anthropogenic radiative forcings considered may help to increase the likelihood of the (still improbable) observations. (Increases in atmospheric moisture supply due to consumptive use within (Figure 1) and outside the basin are far too small to explain the precipitation increase.) We conclude that the precipitation trend is most readily explained mainly as part of an unusually large internal fluctuation in the climate system. This is consistent with findings [*Milly and Dunne*, 1998; *Wetherald and Manabe*, 1999] that regional water-flux changes associated with "greenhouse warming" should not generally be detectable at this time, due to a low signal/noise ratio.

Precipitation and other hydroclimatic variables are positively correlated (Figure 2) with an index of the North Atlantic Oscillation (NAO) [*Hurrell*, 1995], an internal mode of variability that could largely be driving the sequence of processes analyzed herein. In the high-NAO phase, during fall and winter, strengthened southerly winds amplify the transport of water vapor from the Gulf of Mexico into the Mississippi basin, supporting increases in annual-mean atmospheric moisture convergence, precipitation, evaporation, and runoff. The recent NAO trend may or may not be forced; the climate model used in our analysis may have underestimated the response of the NAO to radiative forcing [*Shindell et al.*, 1999] and neglected forcings, e.g., by land-cover change [*Chase et al.*, 2000], may also be relevant.

Concluding remarks

Observed and inferred Mississippi-basin changes in runoff, evaporation, surface net radiation, and pan evaporation, as well as the apparent absence of "greenhouse warming," can be understood as responses to increases in precipitation (mainly) and consumptive water use by humans. Experiments with one climate model suggest that the precipitation trend is explained mainly by natural variability, with only a very small contribution from forcing by changes in greenhouse gases and direct effects of sulfate aerosols. The future intensity of regional precipitation (which correlates with the North Atlantic Oscillation) can be expected to influence thermal and other hydroclimatic conditions in the Mississippi basin. If precipitation returns to historically normal levels, heretofore unrealized "greenhouse warming" could occur in the region. If, on the other hand, precipitation continues its upward course due to some external forcing, then continued intensification of water cycling and suppression of warming in the basin could be expected. In either case, the apparent stabilization or slowing of the growth of consumptive water use [*Solley et al.*, 1998] might contribute a small upward tendency to temperature.

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K. A. Dunne and P. C. D. Milly, U. S. Geological Survey, Geophysical Fluid Dynamics Laboratory/NOAA, P. O. Box 308, Princeton, NJ 08542 (emails: kadunne@usgs.gov, cmilly@usgs.gov)

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