Trends in pan evaporation and reference and actual evapotranspiration across the Tibetan Plateau

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[1] The Tibetan Plateau is one of the areas of the world where humans have had a relatively minor impact. The plateau thus provides ideal conditions for investigating evapotranspiration (In this paper, evapotranspiration terms are defined as follows: (1) "Actual evapotranspiration" includes evaporation from water and soil and transpiration from the vegetation of a specific region; (2) "potential evapotranspiration" includes the maximum quantity of water capable of being evaporated from the soil and transpired from the vegetation of a specific surface; (3) "reference evapotranspiration" includes the maximum quantity of water capable of being evaporated from the soil and transpired from a hypothetical reference grass with an assumed height of 0.12 m, a fixed surface resistance of 70 s m^{-1}, and an albedo of 0.23; and (4) "pan evaporation" means evaporation from open circular pans with a diameter of 20 cm.) issues such as temporal trends of evapotranspiration, the pan evaporation paradox, and the complementary relationship hypothesis. We examined Penman-Monteith reference evapotranspiration and pan evaporation from a 20-cm pan by using a data set from 75 meteorological observatories across the plateau during the period 1966 to 2003. Actual regional evapotranspiration was estimated in 16 catchments across the plateau during the period 1966 to 2001. Reference evapotranspiration and pan evaporation significantly decreased at 47 and 38% of observatories, respectively, though air temperature at most of sites significantly increased ($P < 0.05$); wind speed and sunshine hours significantly decreased at 85 and 43% of observatories ($P < 0.05$). The annual reference evapotranspiration and pan evaporation averaged from all the observatories significantly decreased ($P < 0.05$) while actual annual evapotranspiration averaged from all the catchments increased ($P < 0.1$), indicating the existence of a pan evaporation paradox on the plateau. The analysis with a recovered stationary series method showed that decreasing trend in reference evapotranspiration was due to a decrease in wind speed and a decrease in net total radiation, and the increase in air temperature, however, showed little correlation with the declining trends in reference evapotranspiration and pan evaporation. Regional actual evapotranspiration and reference, Penman potential evapotranspiration, or pan evaporation exhibit complementary behavior, which, however, does not support Bouchet's complementary hypothesis, perhaps because of the very low vapor pressure deficit. The current study suggests that the Bouchet's complementary relationship needs to be reconsidered at high elevations.

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1. Introduction

[2] Pan evaporation (ET_{pan}), a surrogate of potential evapotranspiration (ET_p), is reported to have decreased in different regions in the world since the 1950s [*Chattopadhyay and Hulme*, 1997; *Golubev et al.*, 2001; *Hobbins et al.*, 2004; *Lawrimore and Peterson*, 2000; *Liu et al.*, 2004; *Liu and Zeng*, 2004; *Peterson et al.*, 1995]. This declining trend in ET_{pan} is, however, contrary to the expected effect of global warming, because an elevation of surface temperature is expected to increase ET_p. Two hypotheses have been proposed to explain this contradiction. One is the so-called complementary relationship hypothesis [*Bouchet*, 1963], and the other is that a decrease in solar radiation or an increase in cloud cover plays a major role in the decrease of ET_p.

[3] According to the complementary relationship hypothesis, there is a feedback mechanism between actual evapotranspiration (ET_a) and ET_p for homogeneous surfaces

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with low advection of heat and moisture. The hypothesis suggests that a decrease in ET_p will result in an increase in ET_a [*Brutsaert and Parlange*, 1998; *Golubev et al.*, 2001; *Hobbins et al.*, 2004; *Lawrimore and Peterson*, 2000; *Ramirez et al.*, 2005]. According to this hypothesis, ET_a is limited only by the available energy on a moist surface where the values of both ET_a and ET_p are close to the wet environmental evapotranspiration (ET_w); ET_a falls below ET_p owing to limited moisture availability, and an amount of excess energy becomes available for sensible heat flux, which warms and dries the atmosphere, resulting in increasing ET_p. *Peterson et al.* [1995] ascribed the decreasing ET_{pan} to a decrease in the diurnal temperature range (daily maximum temperature − minimum temperature). *Roderick and Farquhar* [2002] showed a new proof that the globally observed decreasing solar radiation mainly accounts for the decreasing ET_{pan} trend. These arguments and other recent studies indicate that further studies are needed to test the complementary relationship hypothesis [*Ohmura and Wild*, 2002].

[4] The Tibetan Plateau, the largest geomorphologic unit on the Eurasian continent, extends about 2700 km from west to east and about 1400 km from south to north, for a total area of more than 2.5 million km^2 [*Zheng et al.*, 2000]. The plateau is the highest in the world, averaging more than 4000 m above sea level. The population density on the Tibetan Plateau is only about $4/km^2$, about 1/30 of the average population density in China and far less than that in most countries http://en.wikipedia.org/wiki/List_of_countries_by_population_density). The plateau thus is an ideal target area for investigating the pan evaporation paradox and the complementary relationship hypothesis because anthropogenic impact there has been less than in other areas of the world [*Hobbins et al.*, 2001b].

[5] Climate warming on the plateau in past decades has been suggested by meteorological observation and ice core records [*Liu and Chen*, 2000; *Thompson et al.*, 2000]. The average annual and winter temperatures on the plateau rose about 0.16° and 0.32°C per decade, respectively, from 1955 to 1996 [*Liu and Chen*, 2000]. The climatic warming trend seems more evident on the plateau than globally during the period 1950 to 1993 [*Roderick and Farquhar*, 2002].

[6] We focused on the spatial and temporal variation of one kind of ET_p-Penman-Monteith reference evapotranspiration (ET_0) [*Allen et al.*, 1998], ET_{pan}, and ET_a on the world's highest plateau in this study. Our aims were (1) to examine temporal trends of evapotranspiration and how the trends are affected by net total radiation, wind speed, vapor pressure deficit, and surface air temperature, (2) to validate the pan evaporation paradox and to assess the temporal variation of ET_{pan} or ET_0 in relation to global warming, and (3) to clarify whether potential and actual evapotranspiration follow Bouchet's complementary relationship in high-elevation areas.

2. Data and Analysis Methods

2.1. Data Preparation and Process

[7] Meteorological data were provided by the National Meteorological Information Centre of China (NMIC). There are 75 metrological observatories located on the Tibetan Plateau, comprising the Tibetan Autonomous Region, Qinghai Province, and parts of Sichuan and Gansu provinces (Figure 1). The data used to calculate ET_0 were daily values of precipitation, minimum, maximum, and mean air temperature, wind speed, hours of sunshine, and relative humidity during the period 1966 to 2003. Monthly and annual meteorological data were averaged from daily means. Among the 75 observatories, ET_{pan} data were available from 60. ET_{pan} was measured by using a metal pan, 20 cm in diameter and 10 cm high, which was installed 70 cm above the ground [*Chen et al.*, 2005]. Radiation was recorded at only 11 of the 75 meteorological observatories, while solar radiation was consistently observed together with the other meteorological variables at only seven observatories (Figure 1).

[8] The 16 hydrological stations, widely ranging from southern to northern part of the plateau, were chosen for the current study (Figure 1). Steamflow rates at these stations were observed by Qinghai and Tibetan Hydrological Bureaus and then submitted and compiled into hydrological annuals by the Ministry of Water Resources, China. These data were widely used in estimation of variation of runoff [*Cao et al.*, 2006; *Li et al.*, 1998; *Zhang et al.*, 2006]. These data can be approximately regarded as natural flow data because the human water use is very small in quantity and can thus be ignored in these gauged catchments.

[9] The spike removal method was used to smooth the effect of abrupt changes in the meteorological and ET_{pan} data [*Zhang and Tang*, 2005]. Missing meteorological data were extrapolated by using a 7-day moving window [*Falge et al.*, 2001].

2.2. ET_0 and Its Trend Analysis

[10] The Penman-Monteith ET_0 method is used to estimate ET_p from hypothetical reference grass with an assumed height of 0.12 m, a fixed surface resistance of 70 s m^{-1}, and an albedo of 0.23 [*Allen et al.*, 1998]. The assumptions can be applied to most grassland on the plateau, where the vegetation is similar to short grasslands in its major physical characteristics. The Penman-Monteith ET_0 values are theoretical because the ET_0 method does not consider actual surface soil type and water availability. The method, however, provides a standard to compare evapotranspiration capability under various climatic conditions, and it has been successfully applied at scales from a single basin to the whole of China [*Chen et al.*, 2005; *Gao et al.*, 2006; *Gong et al.*, 2006; *Xu et al.*, 2006].

[11] The Penman-Monteith ET_0 formula [*Allen et al.*, 1998] is expressed as

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T_{mean} + 273}u_2\mathrm{VPD}}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where R_n is the net radiation at the canopy surface (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}) calculated according to the difference of mean daily air temperature between two continuous days [*Allen et al.*, 1998], T_{mean} is the mean daily air temperature at 2 m above ground level (°C), u_2 is the wind speed at 2 m above ground level (m s^{-1}), VPD is the vapor pressure deficit (kPa) (the difference between saturated and actual vapor pressures), Δ is the slope of saturated vapor pressure in relation to air temperature (kPa $°C^{-1}$), and γ is the psychrometric constant (kPa $°C^{-1}$). Data processing followed the methods of the Food and Agriculture Organization of the United Nations (FAO) [*Allen et al.*, 1998].

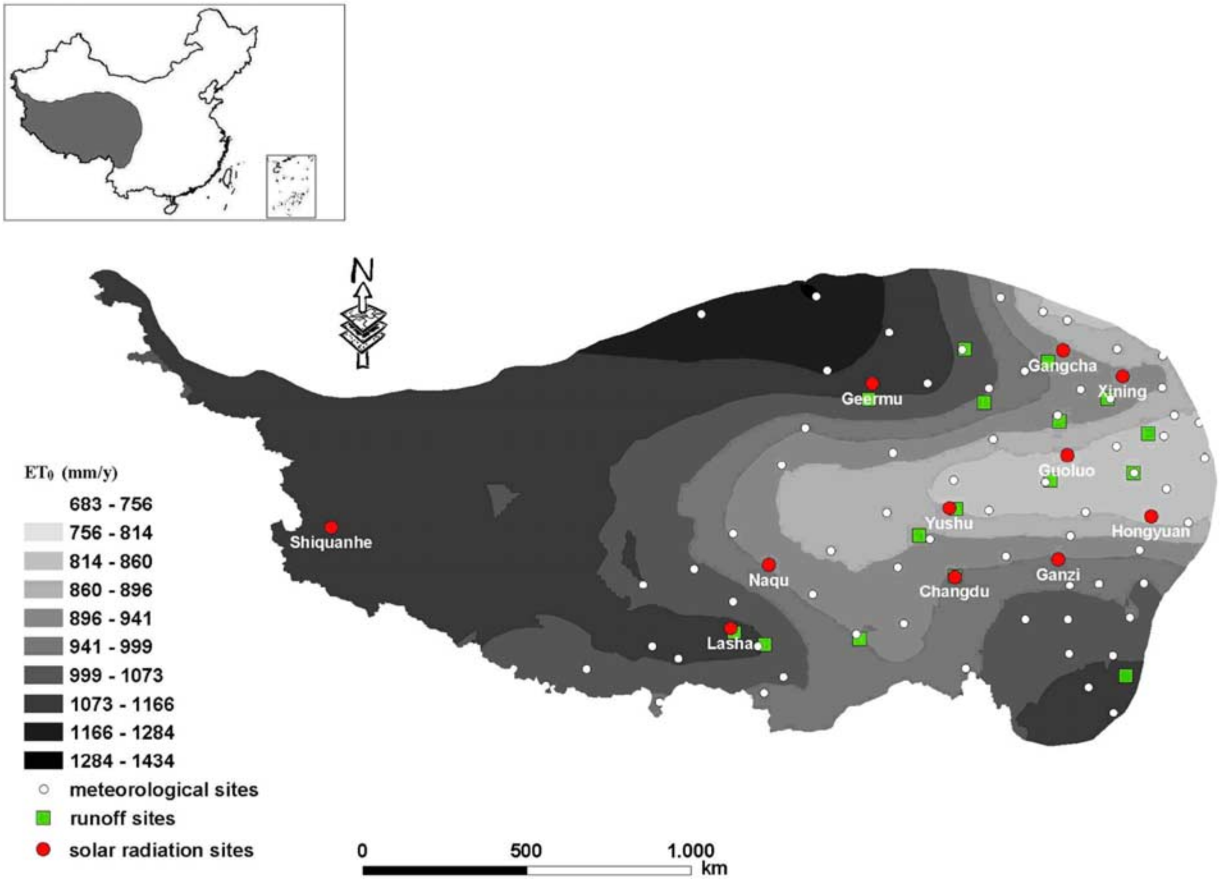

Figure 1. Spatial pattern of the yearly averaged reference evapotranspiration (ET_0) across the Tibetan Plateau and the locations of meteorological observatories and solar radiation observatories.

[12] R_n is a function of solar radiation. We estimated the solar radiation from hours of sunshine (S_{hour}) for those sites without solar radiation records, on the basis of the regression of data from 11 sites:

$$R_s = \left(a_s + b_s \frac{n}{N} R_a\right) \tag{2}$$

where R_s is the solar or short-wave radiation intensity (MJ m^{-2} d^{-1}), n is the actual duration of sunshine (h), N is the maximum possible duration of sunshine or daylight hours (h) (n/N is thus the relative sunshine duration), R_a is the extraterrestrial radiation intensity (MJ m^{-2} d^{-1}), and a_s and b_s are the regression coefficients. The coefficients a_s and b_s at the 11 solar radiation sites were estimated from measured solar radiation and S_{hour} data by using nonlinear least squares data fitting by the Gauss-Newton method (Figure 1).

[13] To assess spatial variation of ET_0 across the plateau, we used a geostatistical module in ARCGIS8.6 to extend the observed results to the whole plateau. In the geostatistical module, the Kriging method with exponential variogram was chosen because of its good performance in mapping ET_0 [*Xu et al.*, 2006].

[14] To quantify the influence of R_n, u_2, and T_{mean} on the decreasing trend in ET_0, a recovered stationary series method [*Xu et al.*, 2006] was applied as follows: (1) Trends in R_n, u_2, and T_{mean} were removed to obtain stationary time series; (2) ET_0 was calculated from the detrended data series; and (3) ET_0 values from the stationary and original time series were compared. The detrended analysis revealed that the decreasing trend in u_2 was the main cause of the decrease of ET_0 on the Tibetan Plateau, and R_n was a secondary cause of the decrease.

2.3. ET_A in a Catchment

[15] Assuming stationarity conditions for the climatic forcing, the net changes of soil water storage should be negligible in terms of the long-term, large-scale water balance in an undisturbed basin [*Hobbins et al.*, 2001b]. Under a control volume including the ground surface, transpirating canopy, and a groundwater aquifer, the steady state water balance over a long term can be expressed as [*Hobbins et al.*, 2001b]

$$ET_a = P_r - RO \tag{3}$$

where P_r is basin-wide precipitation and *RO* is runoff. *RO*, including both surface runoff and groundwater, was estimated from observed stream flows.

2.4. Complementary Relationship

[16] *Bouchet* [1963] hypothesized that there exists a complementary feedback mechanism between ET_a and ET_p. ET_a equals ET_p under wet environmental evapotranspiration (ET_w) conditions. According to the complementary hypothesis [*Bouchet*, 1963], all available energy not used by ET_a goes to heat and dry the overpassing air, driving ET_p

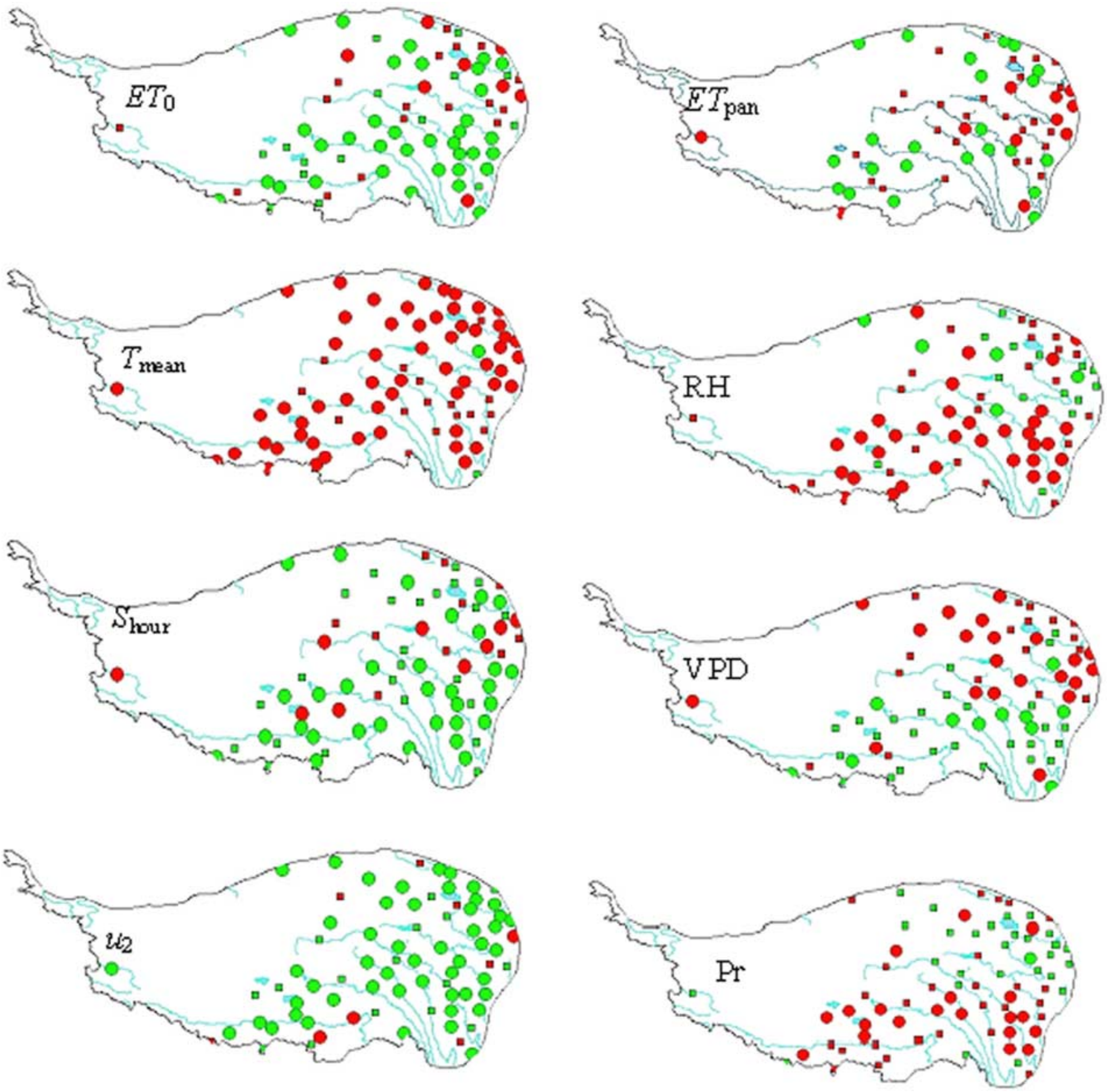

Figure 2. Temporal trends of yearly averages for reference evapotranspiration (ET_0), surface temperature (T_{mean}), hours of sunshine (S_{hour}), wind speed at 2 m above ground level (u_2), relative humidity (RH), vapor pressure deficit (VPD), and precipitation (Pr) for 75 meteorological observatories, and the temporal trend of yearly averaged pan evaporation (ET_{pan}) for 60 observatories across the Tibetan Plateau from 1966 to 2003. Red symbols indicates an increasing trend, and green symbols indicate a decreasing trend; circles and squares represent the trends passing or not passing, respectively, the *F* test at $P < 0.05$.

above ET_w by the amount that ET_a allows it. The complementary relationship is then expressed as

$$ET_a = 2ET_w - ET_p \tag{4}$$

Though ET_0 is a very good representative of ET_p under give conditions, the expression of *Penman* [1948] is used here to estimate the ET_p of Bouchet's hypothesis [*Brutsaert and Stricker*, 1979]. It combines the bulk mass transfer and energy budget for evapotranspiration from a wet surface to calculate ET_p as follows:

$$ET_p = 0.408\frac{\Delta}{\Delta+\gamma}(R_n - G) + 10\frac{\gamma}{\Delta+\gamma}f(u_2)\mathrm{VPD} \tag{5}$$

The units of the parameters and variables here are the same as in equation (1). $f(u_2)$ is estimated by the equation $0.26(1 + 0.54u_2)$ [*Penman*, 1948]. A recent study has shown that the parameters in $f(u_2)$ change seasonally [*Hobbins et al.*, 2001a]. To simplify $f(u_2)$, we used Penman's empirical equation. Here ET_w is calculated by the Priestley-Taylor equation [*Priestley and Taylor*, 1972] as follows:

$$ET_w = 0.408\alpha_{PT}\frac{\Delta}{\Delta+\gamma}(R_n - G) \tag{6}$$

where α_{PT}, the coefficient of the Priestley-Taylor equation, equals 1.26. The approximate value of α_{PT} is 1.26 for a water

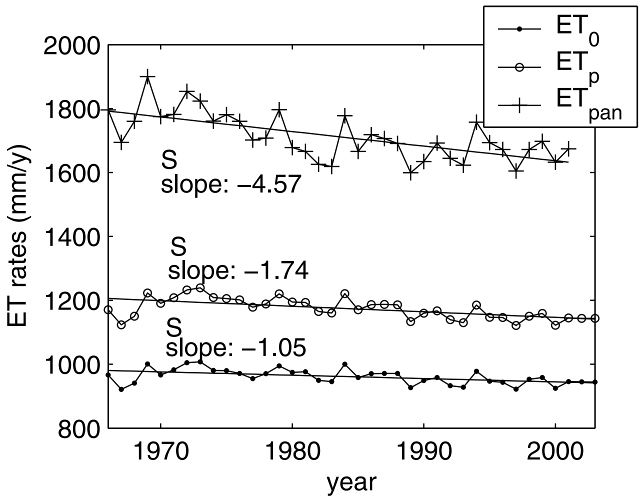

Figure 3. Annual variations in reference evapotranspiration (ET_0), potential evapotranspiration (ET_p), and pan evaporation (ET_{pan}) for the whole plateau from 1966 to 2003. S means significant at $P < 0.05$.

surface under conditions of minimum advection and in the absence of inversions or condensation [*Priestley and Taylor*, 1972]. ET_p by *Penman* [1948] and ET_w by *Priestley and Taylor* [1972] have been successfully applied in an advection-aridity model to study the complementary relationship hypothesis [*Brutsaert and Stricker*, 1979; *Hobbins et al.*, 2001a; *Hobbins et al.*, 2001b].

3. Results

3.1. Trends in ET_0 and ET_{pan} and Environmental Factors

[17] The averaged ET_0 tended to be higher in the western than in the eastern part of the plateau (Figure 1). During the 38-year period, ET_0 decreased significantly at 35 meteorological observatories ($P < 0.05$), but increased at seven observatories (Figure 2). ET_{pan} showed a significantly decreasing trend at 23 out of 60 observatories ($P < 0.05$).

[18] We examined the environmental factors affecting evapotranspiration (Figure 2). T_{mean} showed a significant increase at most meteorological observatories, but u_2 showed a decreasing trend at 85% of observatories, and S_{hour} decreased remarkably at 43% of observatories (Figure 2). Relative humidity increased significantly at about 45% of

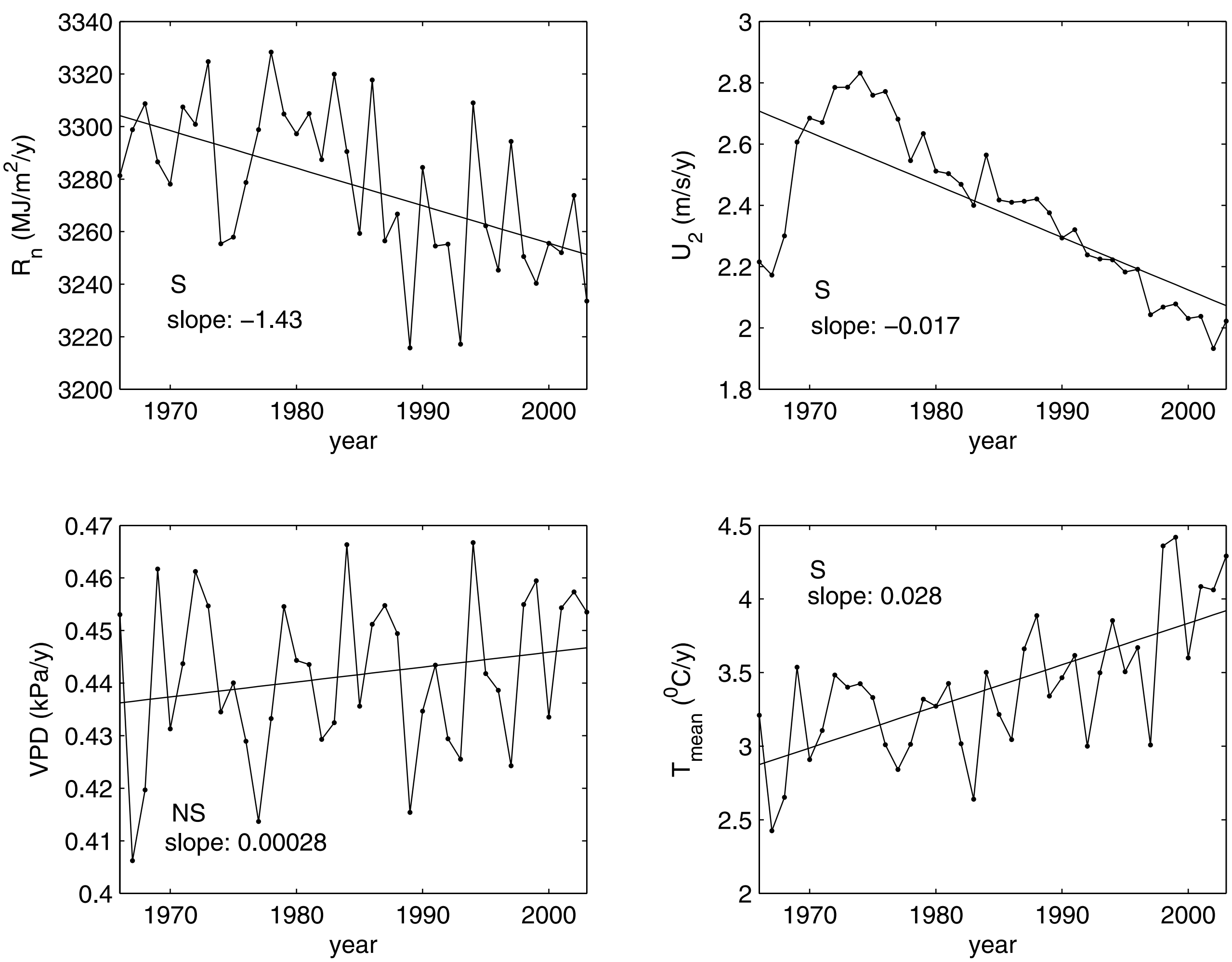

Figure 4. Annual variations in net total radiation (R_n), wind speed (u_2), vapor pressure deficit (VPD), and mean air temperature (T_{mean}) for the whole plateau from 1966 to 2003. S and NS mean significant and not significant, respectively, at $P < 0.05$.

Table 1. Bivariate Correlation Coefficients and Partial Correlation Coefficients Between Annual ET_{pan} and Meteorological Variables Over the Tibetan Plateau

Variable	u_2	R_n	T_{mean}	VPD
Bivariate Correlation Coefficient	0.61[a]	0.38[b]	0.008	0.52
Partial Correlation Coefficient	0.55[a]	−0.07	0.26	0.53[a]

[a]Correlation is significant at the 0.05 level (2-tailed).
[b]Correlation is significant at the 0.01 level (2-tailed).

the observatories, and most of these sites were located in the southern and southeastern parts of the plateau, where there was an evident increasing trend in precipitation (Pr). VPD decreased significantly at only 15% of the sites and showed no significant change at 48% of the sites.

[19] The annual ET_0, ET_p, and ET_{pan} for the whole plateau decreased significantly from 1966 to 2003, with ET_{pan} decreasing at 4.57 mm y^{-2}, ET_p at 1.74 mm y^{-2}, and ET_0 at 1.05 mm y^{-2} (Figure 3). R_n and u_2 also decreased significantly ($P < 0.05$) (Figure 4). T_{mean}, however, increased significantly ($P < 0.05$) at 0.028°C y^{-2}, which is higher than the increasing rate of 0.020°C y^{-2} in the Yellow River Basin [*Liu and Zeng*, 2004]. The increasing trend in T_{mean} contradicts the decreasing trend in ET_0, ET_p, and ET_{pan}, which indicates that the pan evaporation paradox is also likely to exist on the plateau.

[20] Both bivariate and partial correlations suggest that u_2 and VPD are major environmental factors controlling ET_{pan}. Bivariate correlation between R_n and ET_{pan} was significant at the 0.05 level, but T_{mean} was not significantly correlated with ET_{pan} (Table 1).

[21] The detrended variables R_n, u_2, and T_{mean} were used to quantify the impacts of these variables on ET_0 rates (Figure 5). A large positive difference was obtained when subtracting the original ET_0 from ET_0 recalculated with the detrended u_2; a small but still marked positive difference was observed when the original ET_0 was subtracted from ET_0 recalculated with the detrended R_n; a remarkable but negative difference was obtained when subtracting the original ET_0

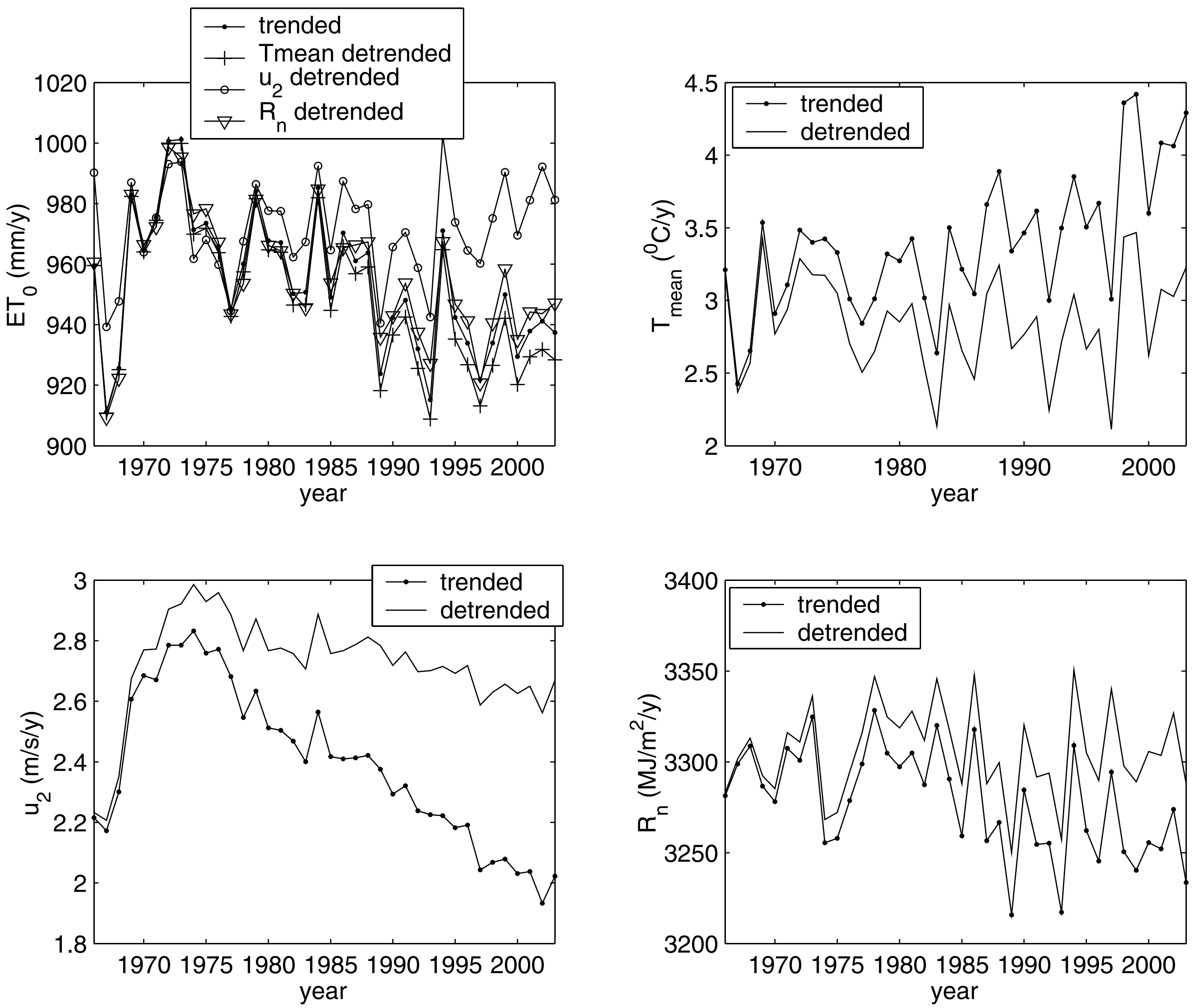

Figure 5. Annual variations in the original annual reference evapotranspiration (ET_0) and ET_0 recalculated from detrended environmental variables, and trended and detrended annual variation of net total radiation (R_n), wind speed (u_2), and mean air temperature (T_{mean}). Values of the variables are averages of data from 75 meteorological sites.

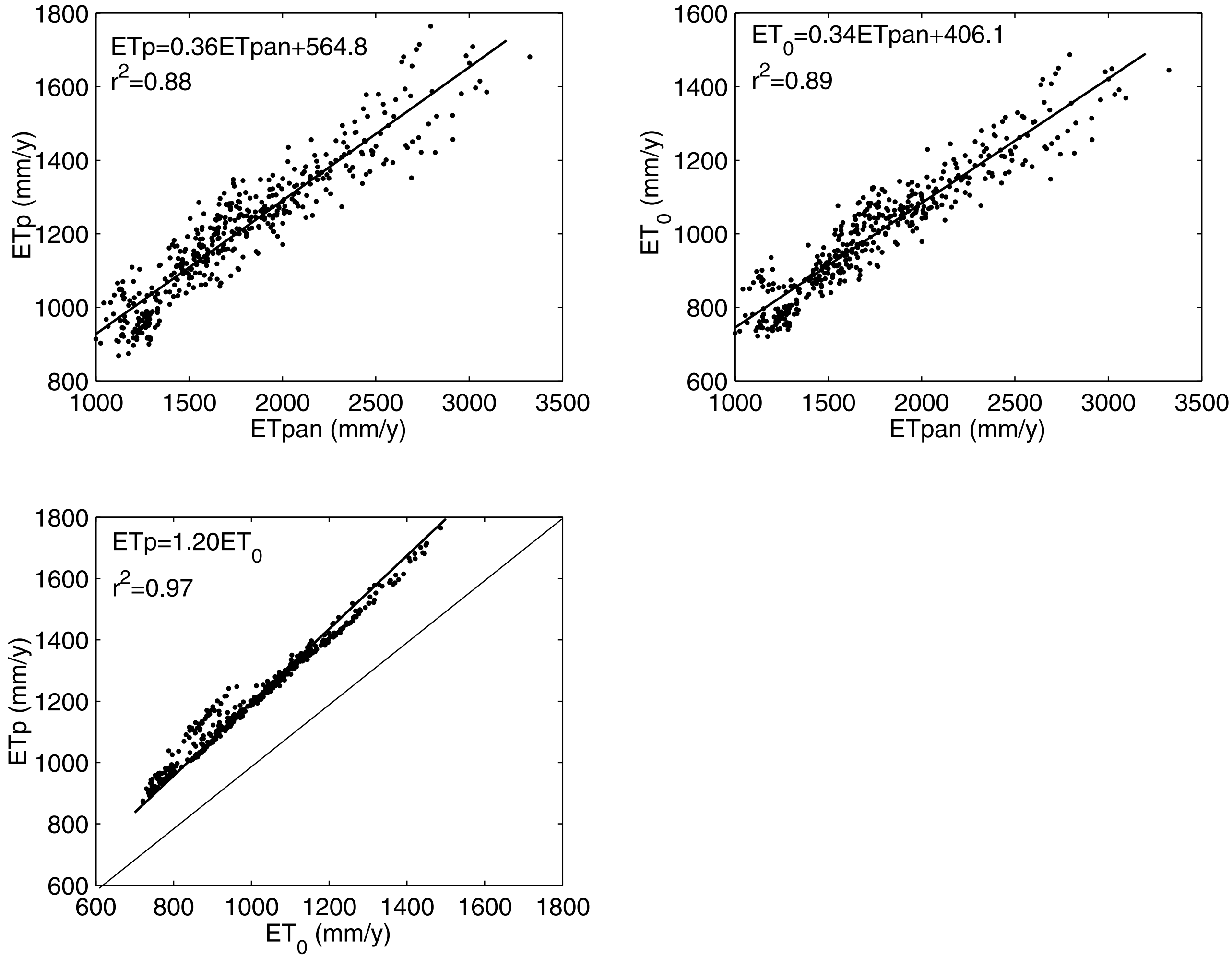

Figure 6. Relationships between Penman-Monteith ET_0, pan-measured evaporation (ET_{pan}), and ET_p calculated by the Penman equation.

from ET_0 recalculated with the detrended T_{mean}. The detrending analysis revealed that the decreasing trend in u_2 was the main cause of the decrease in ET_0 on the Tibetan Plateau, and R_n was a secondary cause of the decrease in ET_0.

3.2. Correlation Between ET_0, ET_{pan}, and ET_p

[22] ET_{pan} is often taken as an indicator of ET_p [*Brutsaert and Parlange*, 1998]. ET_{pan} was highly correlated on a yearly scale with ET_p, obtained with the *Penman* [1948] equation, and with the Penman-Monteith ET_0 (Figure 6). ET_{pan} was significantly correlated with ET_0 at most observatories. A very high correlation ($r^2 = 0.97$) existed between ET_0 and ET_p (Figure 6). The results suggest that ET_{pan} is a good indicator of ET_0 and ET_p on the plateau.

3.3. Spatial Patterns of ET_0 Under Simulated Conditions

[23] To examine how changes in the environmental variables would cause variation in the spatial patterns of ET_0, we arbitrarily changed the environmental variables by increasing or decreasing each value by 10% from the annual means for the period 1966 to 2003. A simulated change of 10% in the environmental variables resulted in large variations in ET_0 at some sites, but resulted in no significant variation at other sites on the plateau (see examples in Figure 7). An increase of T_{mean} by 10% increased ET_0 in the southeastern plateau, but decreased ET_0 in the central part. The decreasing rate of ET_0 was higher in the northwest than in the southeast when we reduced R_s by 10%. A reduction of 10% in R_s resulted in a variation in ET_0 of about 2.1% in the northwestern plateau but a change of about 5.4% in the southeastern plateau. Changes in the spatial pattern of ET_0 were also evident from changes in the other environmental variables (Figure 6).

3.4. Trends of Actual Evapotranspiration and the Complementary Relationship

[24] We collected hydrological data from 16 catchments across the Tibetan Plateau. Among them, 13 watersheds showed an increasing trend in ET_a (Figure 8). The temporal variation trends in ET_a were opposite to those of ET_0 in 9 of the 16 catchments. The averaged ET_a for the 16 catchments was significantly increased ($P < 0.1$) from 1966 to 2001 (Figure 9). If we compare the increasing trend in annual ET_a (Figure 9) with the decreasing trends in annual ET_0, ET_p, and ET_{pan} (Figure 3), we can further find the pan evaporation paradox between ET_a and ET_0 or ET_{pan}.

[25] To determine whether the pan evaporation paradox is caused by Bouchet's complementary relationship between the regional ET_a and ET_p or ET_0, we examined the relation-

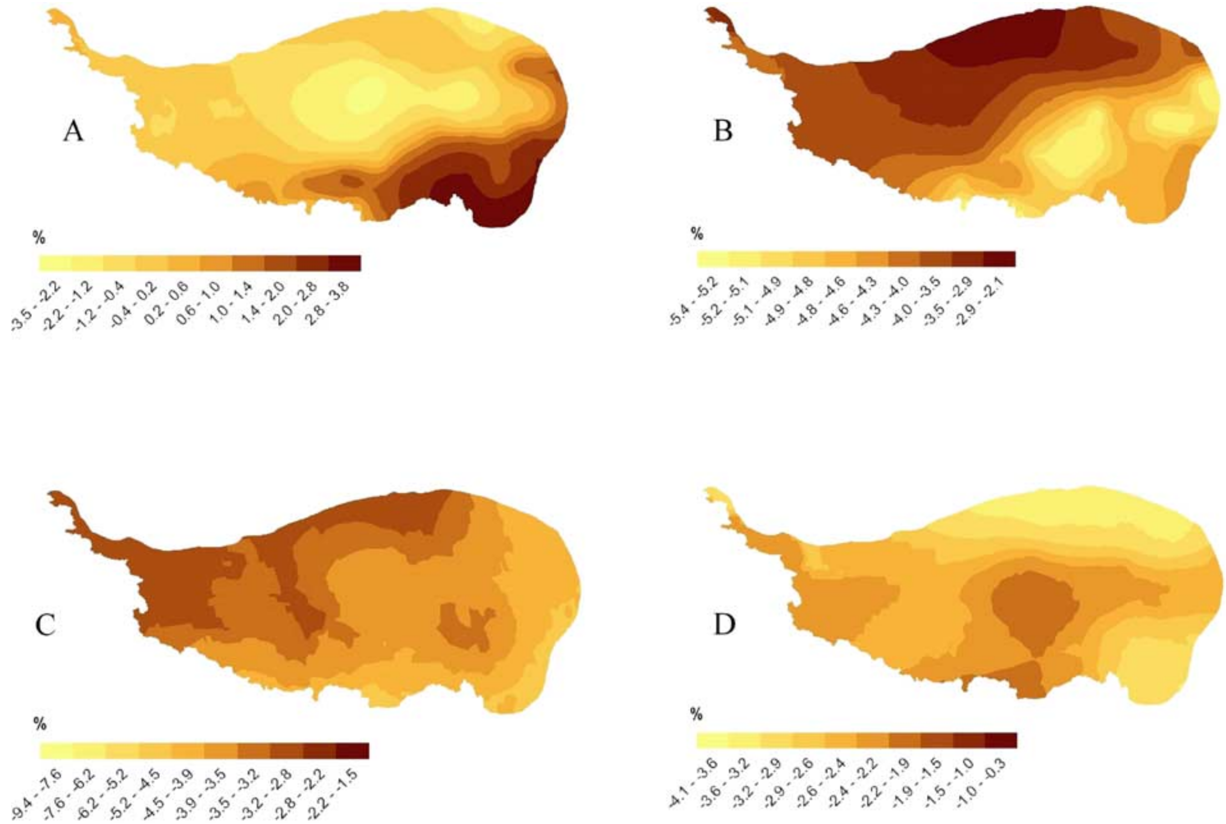

Figure 7. (a) Spatial pattern of ET_0 (%) under simulated conditions resulting from increasing mean air temperature by 10%, (b) decreasing solar radiation by 10%, (c) increasing the relative humidity by 10%, and (d) reducing wind speed by 10% from the annual averaged values at the 75 sites across the Tibetan Plateau in 1966–2003.

ship between standardized precipitation and standardized ET rates and found an apparent complementary relationship (Figure 10). The highest values of ET_p, and ET_0 and ET_{pan}, were observed in the northwest plateau, where the environments are water limited and ET_a is low. With the increase of soil water availability toward the southeast plateau, the standardized ET_a rates increased as the standardized ET_0, ET_p, and ET_{pan} rates decreased. Standardized ET_0 and ET_p tended to converge with ET_a under the highest soil water availability conditions. However, the asymmetrical standardized ET_p and ET_a distribution along the axis-standardized ET_w showed that ET_p was close to ET_w, while ET_a was far from ET_w. The ratio of $ET_a + ET_p$ to ET_w was only about 1.46, far less than 2.0 [equation (4)].

4. Discussion

[26] Despite their critical importance for the global and regional climates, ET_0 and ET_{pan} on the Tibetan Plateau have received little attention. Using data from four observatories, [*Xu et al.*, 2005] reported an increasing ET_{pan} trend across the Tibetan Plateau during 1970–2000. The spatial pattern of ET_p trends was also examined previously from a data set from six observatories across the plateau [*Thomas*, 2000]. With an intensive data set, however, we found that ET_0 and ET_{pan} decreased at most observatories (Figure 2), and the averages of ET_0, ET_p, and ET_{pan} from all of the observatories on the plateau showed a significant decrease (Figure 3). Moreover, the declining rate of ET_{pan}, −45.7 mm per decade across the plateau obtained in the current study is much higher than the rate of −26.3 mm per decade, on the basis of data from eight observatories, reported by *Liu et al.* [2004]. The large data set in the current study provided

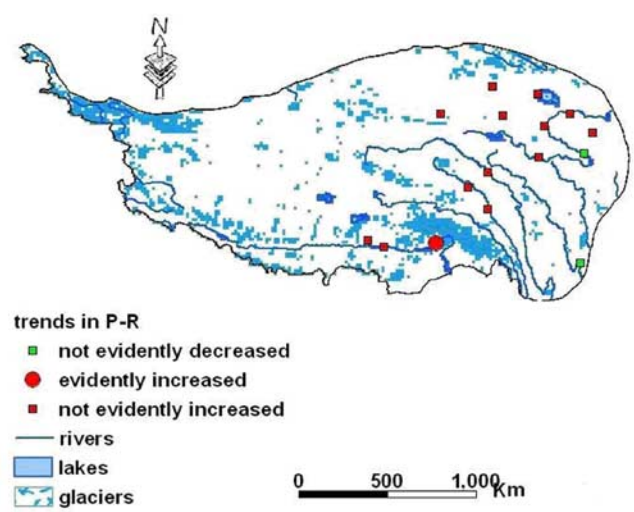

Figure 8. Temporal changes in the actual evapotranspiration indicated by the difference between yearly precipitation (Pr) and yearly runoff (RO) (Pr − RO) in 16 stream-flow-observed watersheds during the period 1966 to 2001.

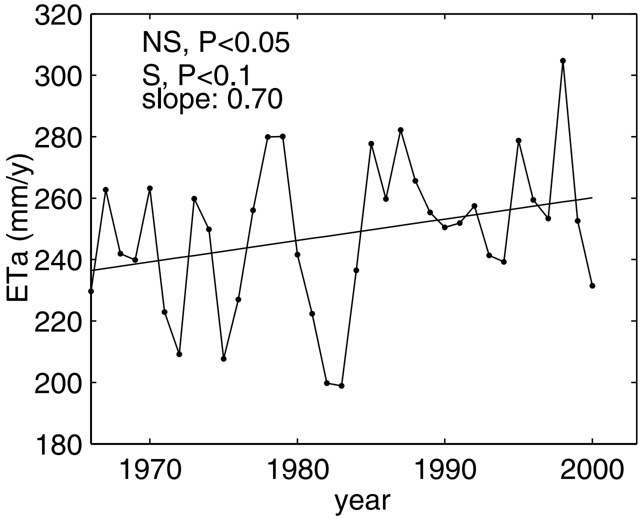

Figure 9. Annual variation in the regional actual evapotranspiration (ET_a). The slope is statistically significant (S) at $P < 0.1$, but it is not statistically significant (NS) at $P < 0.05$.

findings that are greatly different from those of previous studies on the plateau. To assess the spatial and temporal patterns of evapotranspiration on the vast plateau, a database of observations with sufficient spatial and temporal breadth is thus essential.

[27] Solar radiation is an excellent estimator of the radiative budget for ET_0 estimation [*Hobbins et al.*, 2004]. However, owing to lack of enough observational data, we estimated R_s from S_{hour} [equation (2)]. The estimated R_s values compared very well with the measured ones, with high correlation coefficients (r^2 ranged from 0.73 to 0.97) and small root mean square errors (RMSEs) (Figure 11). However, since S_{hour} is determined by a threshold of radiation, R_s may be biased at those sites with more overcast days or even at sites where impacts of aerosols are more evident. For example, R_s was sometimes overestimated at Lasha and Changdu. We further examined the declining trends in the measured R_s and the R_s estimated from S_{hour} (Figure 12). The declining rate of estimated R_s was only slightly higher than that of measured R_s. This result indicates that it is reasonable to use the duration of sunshine to estimate R_s on the plateau. In addition, the result also suggests that aerosols likely play a negligible role in the radiation budget on the plateau.

[28] Both the Penman-Monteith ET_0 and the Penman ET_p methods can combine radiative energy and advective budgets to estimate evapotranspiration from a wet surface. The Penman ET_p method can be applied to different surface types. The Penman-Monteith ET_0, however, is applicable only for estimating ET_p from a hypothetical surface of green grass of uniform height, actively growing, and well watered [*Allen et al.*, 1998]. In the current study, ET_p was highly correlated with the Penman-Monteith ET_0, with ET_p/ET_0 having a slope of 1.2 (Figure 6). Penman-Monteith ET_0 is also often used as a standard for verifying and calibrating ET_{pan} [*Chen et al.*, 2005]. The good correlation between ET_0 and ET_{pan} on the plateau indicates that ET_{pan} can be a good measure for ET_0 or ET_p (Figure 6).

[29] Although there was a marked increase in surface air temperature, ET_0 averaged across the 75 sites showed a decreasing trend (Figure 3). In the sensitivity analysis, an increase in air temperature of 10% resulted in a decrease in ET_0 over large areas of the plateau (Figure 7a). This result can be explained by the fact that increasing temperature causes a simultaneous increase in both VPD and outward long-wave radiation. The increase in VPD increases advective water transfer, while the increase in long-wave radiation decreases R_n. ET_0 declines when the amount of increase in ET_0 caused by the increase in VPD is lower than the amount of decrease in ET_0 caused by the increase in long-wave radiation under low air temperature conditions. The impact on ET_0 is the reverse under high air temperature conditions. Air temperature on the plateau decreases gradually from the southeast to the northeast owing to a gradual increase in elevation. Therefore a +10% rise of temperature causes an evident increase in ET_0 in the southeastern plateau, a

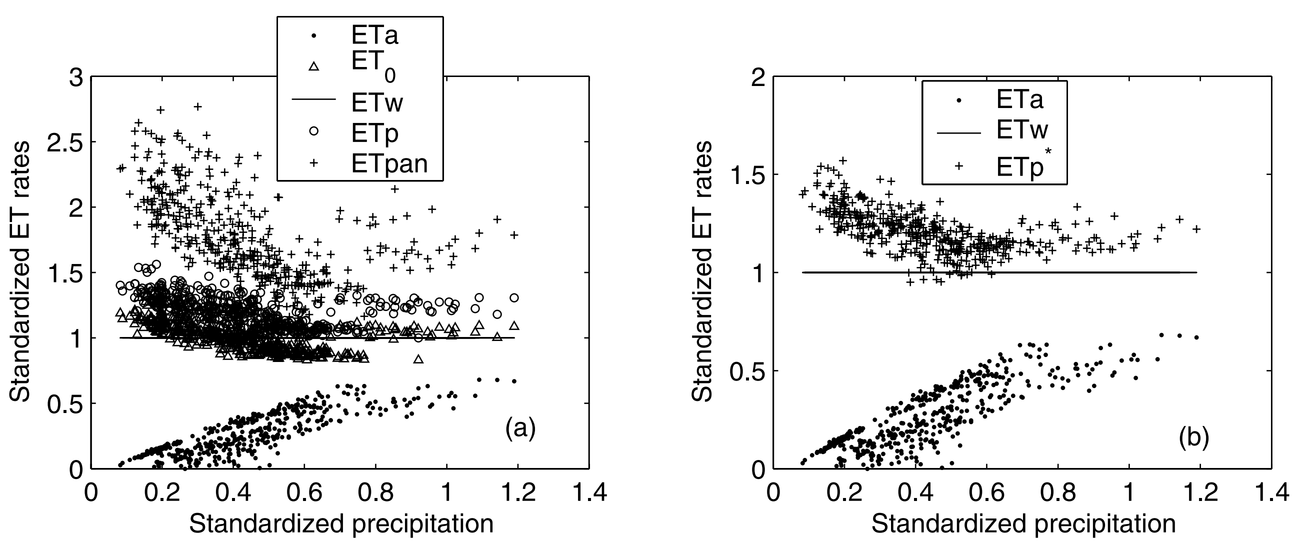

Figure 10. Complementary relationship diagrams. ET rates and precipitation have been standardized by expressing them as a fraction of ET_w. ET_p^* was calculated from ET_{pan} from the equation of the regression of ET_p against ET_{pan} (see Figure 5).

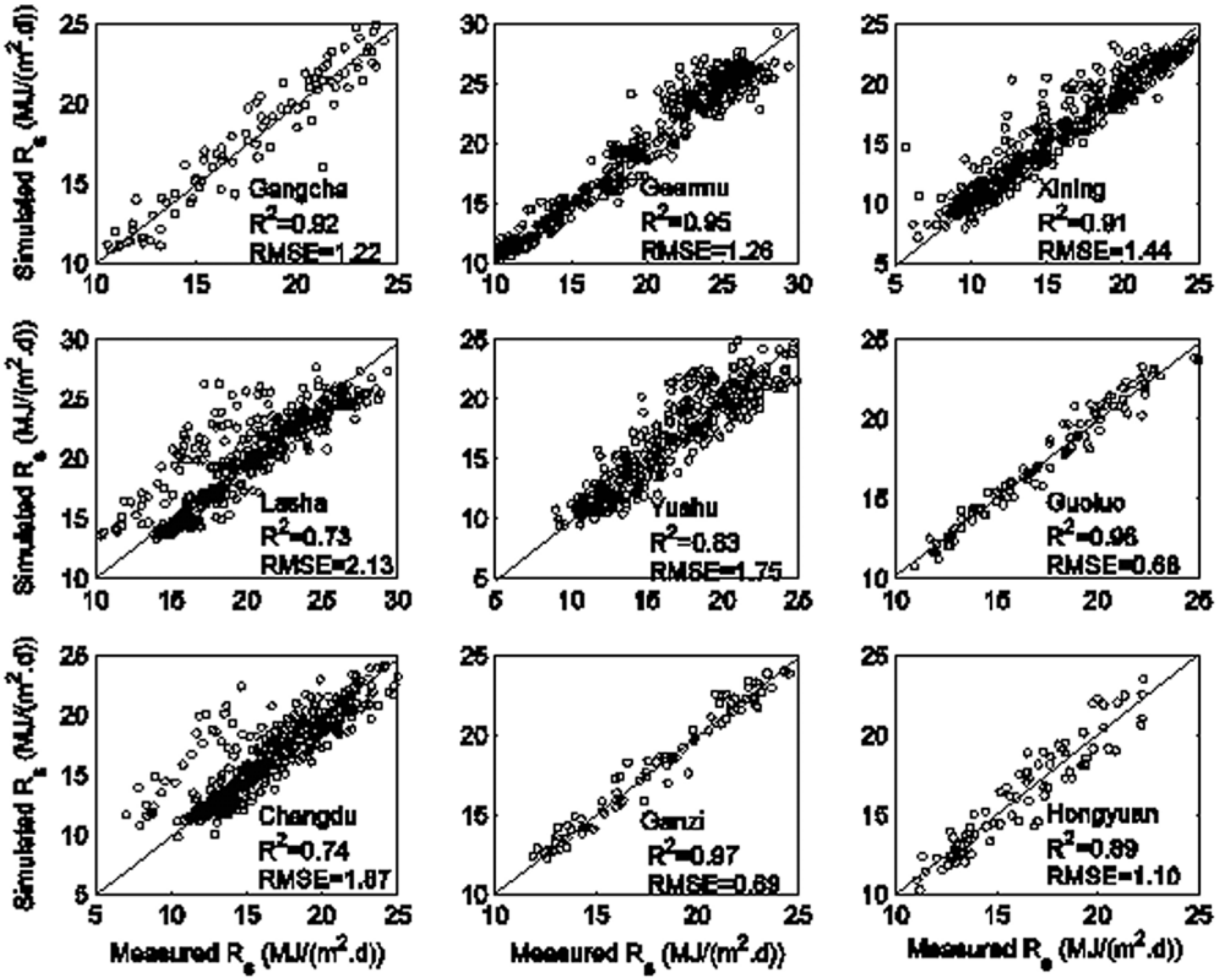

Figure 11. Comparison of the measured solar radiation intensity (R_s) with R_s estimated from the actual duration of sunshine [see equation (2)] at solar radiation observatories across the Tibetan Plateau (see names of sites from Figure 1). RMSE is root mean square error, and the units are MJ m^{-2} d^{-1}.

decrease in ET_0 in the central plateau, but no significant change in ET_0 in the western and northern plateau. These results suggest that elevation of the surface temperature may have very limited effects on ET_0 across large areas of the plateau.

[30] Annual ET_a rates were quantified by using annual rainfall and streamflow rates [equation (3)]. The influence of glacier was not taken into account because of the facts that there were no available data of discharge from melted glacier and the influence is very limited in most of the selected catchments (Figure 8). Owing to evident global warming and glacier's retreat across the large areas of plateau [*Thompson et al.*, 1997; *Tian et al.*, 2006], it is reliable to assume that discharge rate from melted glacier should have increased in the last 40 years. If this is the case for the selected 16 catchments in this study, the conclusion that the averaged ET_a for the catchments increased significantly (Figure 9) would be further strengthened.

[31] The pan evaporation paradox clearly exists on the highest plateau. We tried to explain the paradox by using Bouchet's complementary relationship, but found that the hypothesis of 1:1 compensation was not appropriate on the

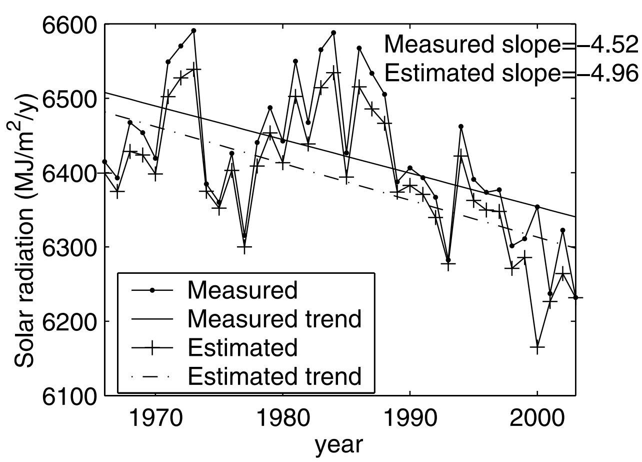

Figure 12. Annual variation of the measured solar radiation intensity (R_s) and R_s estimated from duration of sunshine from 1966 to 2003; both are averages of data from the seven long-term radiation stations. The units of the slopes are MJ m^{-2} y^{-1}.

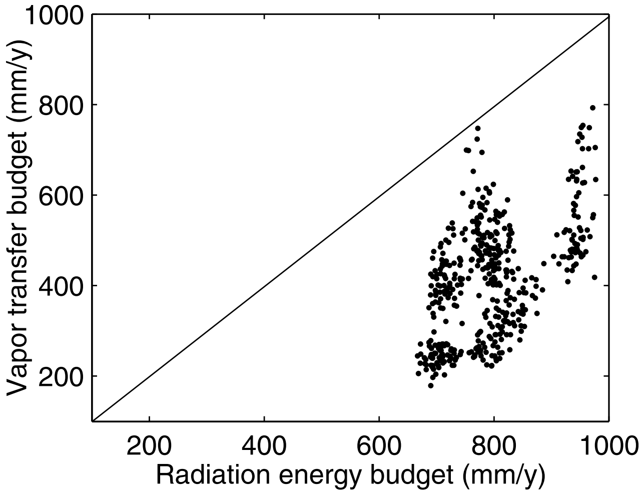

Figure 13. Comparison of the vapor transfer budget and the radiative energy budget for the 16 test watersheds.

highest plateau. The ratio of $ET_a + ET_p$ to ET_w is much lower than two. This ratio is a function of stomatal resistance and aerodynamic resistance [*Sugita et al.*, 2001]. As defined by Bouchet's hypothesis, it is strictly equal to two only when the stomatal resistance is at a minimum or the surface is smooth. The surface of the Tibetan Plateau is far from flat, situated, as it is, among several huge mountain ranges, including the Himalayas, the Kunlung mountains, and the Tanggula mountains. The heterogeneous landscape more or less influences the application of Bouchet's complementary relationship.

[32] The weak vapor-transfer budget seems to provide a major explanation for Bouchet's hypothesis on the plateau. According to the hypothesis, if ET_a falls below ET_w because of low water availability, an amount of excess energy ($Q = ET_w - ET_a$) becomes available, resulting in an increase in sensible heat flux. The heat flux increases ET_p by warming and drying the atmospheric boundary layer. However, if the air drying power is too weak to increase ET_p, then the increase of ET_p must be less than the value of $ET_w + Q$. This situation results in a low value of less than two for the ratio of $ET_a + ET_p$ to ET_w. This is the case on the Tibetan Plateau where VPD is much less than the value in the lowlands because of the low surface temperatures at high elevation. VPD during the warm season (May–September) over the whole of China varied from 0.80 to 0.95 kPa during 1955–2000 [*Liu et al.*, 2004], while the warm season VPD over the plateau varied only from 0.52 to 0.62 kPa during 1966–2003. Of the two terms of the ET_p equation [equation (5)], the vapor transfer budget is much less than the radiation energy budget on the plateau (Figure 13). In such low-VPD environments, Bouchet's hypothesis will not hold true. For instance, in the extreme case of an arid environment on the plateau, ET_a is close to zero while ET_p does not reach a value of $2ET_w$ owing to the weak drying power.

5. Conclusions

[33] The present study showed that ET_0 and ET_{pan} declined in large areas of Tibetan Plateau and ET_0 and ET_{pan} averaged from the whole plateau also significantly decreased, which was mainly contributed by a reduction of wind speed. Decreases in ET_0 or ET_{pan} have previously been reported to be caused in part by reductions of wind speed [*Chen et al.*, 2005; *Gao et al.*, 2006; *Xu et al.*, 2006]. The present study further strengthens the point. The reduction of surface wind speed may indicate the weakening of regional atmospheric circulation. However, all these researches are focused at local scales. There are seldom reports on the weakening by regional or global circulation models. The reductions of wind speed and ET_0 on the plateau should be paid much attention in these models.

[34] With an increase of surface temperature, ET_{pan} evidently decreased, but ET_a increased markedly, suggesting the existence of the pan evaporation paradox over the Tibetan Plateau. ET_a and ET_{pan}, ET_0, or ET_p exhibit a complementary relationship, but not Bouchet's complementary relationship. It seems that the paradox can be explained by the air-drying power being much smaller than the radiative energy. The current result and those of other recent studies all suggest that the causes of variation in evapotranspiration are far from settled. The results of this study suggest that the complementary relationship between ET_p and ET_a should be incorporated into climate or boundary layer models in order to predict evapotranspiration in the field.

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