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Identification of dominant climate factor for pan evaporation trend in the Tibetan Plateau

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Abstract: Despite the observed increase in global temperature, observed pan evaporation in many regions has been decreasing over the past 50 years, which is known as the “pan evaporation paradox”. The “pan evaporation paradox” also exists in the Tibetan Plateau, where pan evaporation has decreased by 3.06 mm a^{-2} (millimeter per annum). It is necessary to explain the mechanisms behind the observed decline in pan evaporation because the Tibetan Plateau strongly influences climatic and environmental changes in China, Asia and even in the Northern Hemisphere. In this paper, a derivation based approach has been used to quantitatively assess the contribution rate of climate factors to the observed pan evaporation trend across the Tibetan Plateau. The results showed that, provided the other factors remain constant, the increasing temperature should have led to a 2.73 mm a^{-2} increase in pan evaporation annually, while change in wind speed, vapor pressure and solar radiation should have led to a decrease in pan evaporation by 2.81 mm a^{-2}, 1.96 mm a^{-2} and 1.11 mm a^{-2} respectively from 1970 to 2005. The combined effects of the four climate variables have resulted in a 3.15 mm a^{-2} decrease in pan evaporation, which is close to the observed pan evaporation trend with a relative error of 2.94%. A decrease in wind speed was the dominant factor for the decreasing pan evaporation, followed by an increasing vapor pressure and decreasing solar radiation, all of which offset the effect of increasing temperature across the Tibetan Plateau.

Keywords: pan evaporation trend; reference evapotranspiration; attribution; the Tibetan Plateau

1 Introduction

Pan evaporation is a measure of the evaporative demand over terrestrial surfaces. One of the expected consequences of global warming is that the increasing near-surface air temperature should lead to the increased evaporative demand (Roderick *et al*., 2009). However, decreases in pan evaporation over the last years have been reported in the United States (Peterson *et al*., 1995), former Soviet Union (Peterson *et al*., 1995; Golubev *et al*., 2001), China (Liu *et al*., 2004; Xu *et al*., 2006; Wang *et al*., 2007; Zheng *et al*., 2009), Canada (Burn and

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Hesch, 2007), Australia (Roderick and Farquhar, 2004; Roderick *et al*., 2007; Rayner 2007), New Zealand (Roderick and Farquhar, 2005), India (Chattopadhyay and Hulme, 1997), Thailand (Tebakari *et al*., 2005), Ireland and United Kingdom (Stanhill and Möller, 2008). The increasing temperature accompanying with decreasing pan evaporation was called "pan evaporation paradox" (Brutsaert and Parlange, 1998), which has attracted many research interests during the past decade.

The explanations of the "pan evaporation paradox" have been concluded in different regions using different methods (Table 1). The three methods are generally used in the literature: the correlation analysis, detrending and derivation based approach. The correlation analysis method calculates the correlation coefficients between evaporation and climate factors (Liu *et al*., 2004; Burn and Hesch 2007; Stanhill and Möller, 2008), or derive a regression equation between them (Chattopadhyay and Hulme, 1997). Therefore, the higher the correlation coefficients between a climate factor and the evaporation, the impact of the factor on the change of evaporation is more important. The detrending method, on the other

Table 1 Pan evaporation trend, attribution method and dominant factor of change in pan evaporation from various regions

Region and period	Pan type[a], site number	E_{pan} trend (mm a^{-2})	Attribution method[b]	Dominant factor[c]	Reference
USA, 1948–1993	Class-A, 746	–2.2	CA	DTR	Peterson *et al*., 1995
India, 1961–1992	Class-A, 19	–12	CA	RH	Chattopadhyay and Hulme, 1997
Former Soviet Union, 1960–1990	Class-A, 8	–3.7	CA	DTR	Golubev *et al*., 2001
China, 1955–2000	ϕ20, 85	–2.9	CA	R_s	Liu *et al*., 2004
Yangtze River Basin China, 1960–2000	ET_{ref}, 150	–3.1	Detrend	R_s	Xu *et al*., 2006
Yangtze River Basin China, 1961–2000	ϕ20, 115	–3.0	CA	R_s	Wang *et al*., 2007
Haihe River Basin China, 1957–2001	ϕ20, 45	–4.9	CE	U	Zheng *et al*., 2009
Tibetan Plateau, 1966–2003	ϕ20, 75	–4.6	Detrend	U	Zhang *et al*., 2007
Tibetan Plateau, 1961–2000	ET_{ref}, 101	–1.3	CA	U	Chen *et al*., 2006
Australia, 1975–2004	Class-A, 41	–2.0	CE	U	Rodick *et al*., 2007
Australia, 1975–2004	Class-A, 17	–4.0	Detrend	U	Rayner, 2007
Thailand, 1982–2001	Class-A, 27	–10.5	No analysis		Tebakari *et al*., 2005
New Zealand, 1970s–2000	Class-A, 19	–2.0	No analysis		Roderick and Farquhar, 2005
Canada, 1965–2000 (May to Septemeber)	Class-A, 4	–1.0	CA	U	Burn and Hesch, 2007
Ireland, 1965–2002	Class-A, 8	4 decrease, 4 increase	CA	R_s	Stanhill and Möller, 2008
UK, 1900–1968	MO tank, 8	6 decrease, 2 increase	CA	R_s	Stanhill and Möller, 2008

[a] Pan type: "Class-A" means the US Weather Bureau's Class-A pan, which is circular, 120.7 cm in diameter and 25.4 cm in depth and mounted 15 cm above ground level (Brouwer and Heibloem, 1986). "ϕ20" means a metal pan, 20 cm in diameter and 10 cm high, installed 70 cm above the ground (Fu, 2004). "MO tank" means British Meteorological Office (MO) tank, 180 × 180 × 60 cm, installed 6 cm above the surrounding soil (Symons, 1867). "ET_{ref}" means calculated reference evapotranspiration by Penman-Monteith method (Allen, 1998).

[b] Attribution Method: "CA" means correlation analysis method. "Detrend" means detrend analysis method. "CE" means combination equation method. All the three methods are introduced in this paper.

[c] Dominant factor: "DTR" means diurnal temperature range. "RH" means relative humidity. "R_s" means solar radiation. "U" means wind speed.

hand, tries to detect the dominant factors for evaporation change by evaluating the effects of the climate factor trends. The detrended climate factors leading to the greatest difference in evaporation is then considered as the main reason of evaporation change (Xu *et al*., 2006; Zhang *et al*., 2007; Rayner, 2007). The derivation based approach, which depends on the derivation coefficients of evaporation to climate factors, most recently had been successfully used in quantifying the contribution of climate factors to evaporation changes (Roderick and Farquhar, 2002; Roderick *et al*., 2007; Zheng *et al*., 2009).

The Tibetan Plateau plays an important role in climate change because it shows critical impacts on climate in Asia and elsewhere in the Northern Hemisphere (Ma *et al*., 2009). Long-term decreasing trend of pan evaporation had been detected in the Tibetan Plateau (Zhang *et al*., 2007), which implicated a change of energy budget in the Plateau. It has been reported that, on top of temperature, wind speed may be the dominant factor for pan evaporation change in the Plateau. The conclusion was drawn basing on the correlation analysis (Chen *et al*., 2006) and the detrend method (Zhang *et al*., 2007). It was great impressive but did not quantitatively provide the contribution rate of each climate factors to change in pan evaporation.

The purpose of this paper is to quantitatively assess the impacts of climate factor on the observed changes in pan evaporation in the Tibetan Plateau, regarding solar radiation, temperature, vapor pressure and wind speed. The spatial patterns and interannual variation of the contribution rate for each climate factors to the pan evaporation change across the Tibetan Plateau will also be addressed.

2 Study area and data

The Tibetan Plateau, known as “the Roof of the World”, is the largest geomorphologic unit on the Eurasian continent. The Tibetan Plateau extends approximately 2700 km from west to east and 1400 km from south to north, with a total area of more than 2.5 million km^2 (Zheng *et al*., 2000). In recent years, significant climate change was detected in the Tibetan Plateau, such as the maximum and minimum temperatures were increasing with diurnal temperature range decreasing, annual precipitation and vapor pressure deficits were also increasing (Xie *et al*., 2010), surface solar radiation was decreasing after the 1980s (You *et al*., 2010), snow cover fraction was slightly decreasing (Pu and Xu, 2009), glacier was shrinking (Piao *et al*., 2010). The climate change in the Tibetan Plateau has strongly affected its environment and is closely related to global climate change (Zheng and Li, 1999).

In this study, the routine meteorological records of 75 national meteorological stations for the period from 1970 to 2005 were used (Figure 1). The dataset retrieved from the National Climatic Centre (NCC) of China Meteorological Administration (CMA) includes daily observations of maximum, minimum and average air temperature (T_{max}, T_{min}, T_{mean}) at 2 m height, wind speed (U) measured at 10 m height, vapor pressure (VP) at 2 m height, sunshine duration, precipitation and pan evaporation (E_{pan}). E_{pan} was measured using a metal pan, 20 cm in diameter and 10 cm high, installed 70 cm above the ground. Elevations of the 75 stations vary between 1583 m (No.56533) and 4800 m (No.55294), and the elevations of 50 stations are above 3000 m. Of the 75 stations, 11 have solar radiation records. To estimate the reference evapotranspiration, the measured wind speed was transferred to wind

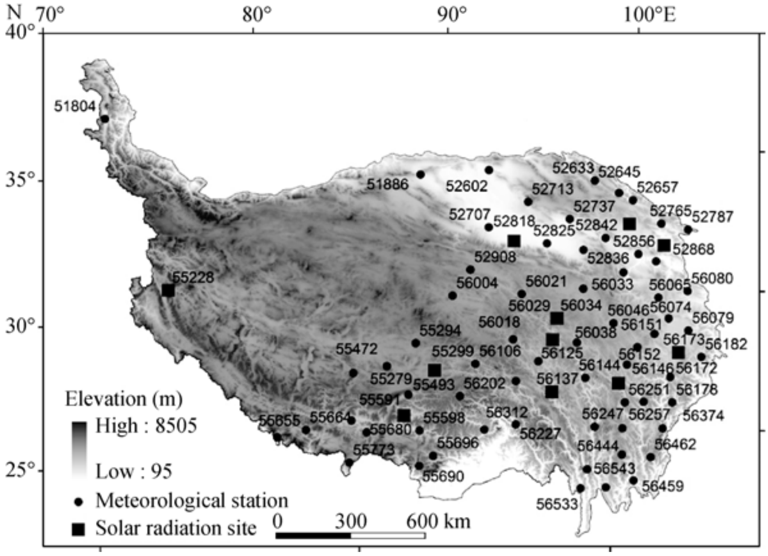

Figure 1 Map of the Tibetan Plateau and location of the meteorological stations (Squares indicate meteorological stations with solar radiation data)

speed at 2 m height by the wind profile relationship introduced by Allen *et al.* (1998). For the entire Plateau, the average values were obtained by the Kriging interpolating method in ArcGIS9.3 based on the station observation.

3 Methodology

3.1 Trend detection

The rank-based non-parametric Mann–Kendall statistical test (Mann, 1945; Kendall, 1975) has been commonly used for trend detection (Yue and Wang, 2002; Zheng *et al.*, 2007) due to its robustness for non-normally distributed and censored data, which are frequently encountered in hydro-climatic time-series. In this paper, the method was used to detect the trends of pan evaporation, temperature, solar radiation, vapor pressure and wind speed in the Tibetan Plateau. At the significant level of $\alpha=0.05$, a positive Mann-Kendal statistics Z larger than 1.96 indicates an significant increasing trend, while a negative Z lower than –1.96 indicates a significant decreasing trend.

The linear regression approach was used to detect the trend of series x against time t. For the linear regression function (i.e. $x=a+bt$), we have $dx/dt=b$, in which the slope b can be considered an indicator describing the trend of the variable concerned and estimated as:

$$b=\left[n\sum_{i=1}^{n}x_i t_i-\left(\sum_{i=1}^{n}x_i\right)\left(\sum_{i=1}^{n}t_i\right)\right]\Bigg/\left[n\sum_{i=1}^{n}t_i^2-\left(\sum_{i=1}^{n}t_i\right)^2\right] \tag{1}$$

3.2 Trend attribution

For a function $y=f(x_1, x_2,\ldots)$, the variation of the dependent variable y can be expressed by the differential equation as:

$$dy = \sum \frac{\partial f}{\partial x_i} dx_i = \sum f_i' dx_i \tag{2}$$

where x_i is the *ith* independent variable and $f_i' = \partial f / \partial x_i$. Moreover, as y varies with time t, we can rewrite Eq.(2) as:

$$\frac{dy}{dt} = \sum \frac{\partial f}{\partial x_i} \frac{dx_i}{dt} = \sum f_i' \frac{dx_i}{dt} \tag{3}$$

let $TR_y = dy/dt$ and $TR_i = dx_i/dt$ be the long-term trend in y and x_i, then Eq.(3) can be rewritten as:

$$TR_y = \sum f_i' TR_i = \sum C(x_i) \tag{4}$$

if TR_y and TR_i are estimated as the slope of the linear regression for y and x_i against time t given in Eq.(1), $C(x_i)$ can then be estimated as the contribution rate of x_i to the long-term trend in y, which exactly equals to the product of partial derivative and long-term trend in x_i.

According to Eq.(4), with known form of the function, it is therefore easy to estimate the contribution rate of x_i to y. In terms of pan evaporation, it is widely accepted that there exists rather good linear relationship with reference evapotranspiration, expressed as:

$$E_{pan} = K_p ET_{ref} + K_c \tag{5}$$

where K_p and K_c are regression coefficients, and E_{pan} is pan evaporation and ET_{ref} is reference evapotranspiration (mm a^{-1}). The reference evapotranspiration is defined as the potential evapotranspiration of a hypothetical surface estimated by the Penman-Monteith method, where the land cover is 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. FAO recommends that reference evapotranspiration can be estimated as (Allen *et al*., 1998):

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T_{mean} + 273} U \cdot (VP_s - VP)}{\Delta + \gamma(1 + 0.34U)} \tag{6}$$

where ET_{ref} is reference evapotranspiration (mm d^{-1}), R_n is net radiation at reference surface (MJ m^{-2} d^{-1}), G is soil heat flux density (MJ m^{-2} d^{-1}), T_{mean} is daily mean temperature (℃), U is the wind speed at 2 meters height (m s^{-1}), VP_s is saturated vapor pressure (kPa), VP is actual vapor pressure (kPa), Δ is the slope of vapor pressure curve versus temperature (kPa ℃$^{-1}$) and γ is psychrometric constant (kPa ℃$^{-1}$). R_n represents the difference between incoming net shortwave radiation (R_{ns}) and outgoing net long-wave radiation (R_{nl}). R_{ns} is estimated from surface solar radiation (R_s):

$$R_{ns} = (1 - \lambda) R_s \tag{7}$$

where λ (=0.23) is the albedo of the reference grassland, alfalfa. R_s is estimated as:

$$R_s = (a_s + b_s \frac{S}{N}) R_a \tag{8}$$

where S is the actual duration of sunshine (h), N is the maximum possible duration of sunshine or daylight hours (h) (S/N is thus the relative sunshine duration), and R_a is the extraterrestrial radiation intensity (MJ m^{-2} d^{-1}). The coefficients a_s (=0.22) and b_s (=0.55) were estimated from measured solar radiation and sunshine hours at the 11 radiation stations (Figure 1) by using nonlinear least squares data fitting by the Gauss-Newton method.

Following Eq.(6), for contribution rate to reference evapotranspiration trend can be approximately estimated below (Zheng *et al*., 2009):

$$\frac{dET_{ref}}{dt}=\frac{\partial ET_{ref}}{\partial R_s}\frac{dR_s}{dt}+\frac{\partial ET_{ref}}{\partial T_{mean}}\frac{dT_{mean}}{dt}+\frac{\partial ET_{ref}}{\partial U_2}\frac{dU}{dt}+\frac{\partial ET_{ref}}{\partial VP}\frac{dVP}{dt}+\delta \tag{9}$$

With the relation between pan evaporation and reference evapotranspiration shown in Eq.(5), the contribution rate of climate factors to long-term trend in E_{pan} can be expressed as:

$$dE_{pan}/dt=K_pC(R_s)+K_pC(T_{mean})+K_pC(U\ )+K_pC(VP)+\varepsilon \tag{10a}$$

or simplified as:

$$TR_{pan}=dE_{pan}/dt=C'(R_s)+C'(T_{mean})+C'(U_2)+C'(VP)+\varepsilon \tag{10b}$$

where TR_{pan} is the long-term trend in E_{pan} and can be estimated with Eq.(1) by the observed data, and $C'(R_s)$, $C'(T_{mean})$, $C'(U)$ and $C'(VP)$ are individual contributions to the long-term trends in E_{pan} due to a change in R_s, T_{mean}, U and VP respectively; ε is the error item. Furthermore, the individual proportional contribution of climate variables to the long-term trend in E_{pan} can be estimated as:

$$\rho(x)=\frac{C'(x)}{C'(R_s)+C'(T_{mean})+C'(U_2)+C'(VP)}\times100\%=\frac{C'(x)}{C_{pan}}\times100\% \tag{11}$$

where x may be R_s, T_{mean}, U or VP, and C_{pan} is the estimated total contribution to the pan evaporation trend.

4 Results

4.1 Relations between ET_{ref} and E_{pan}

Figures 2 and 3 show the correlation between annual E_{pan} and ET_{ref}. As shown in Figure 2,

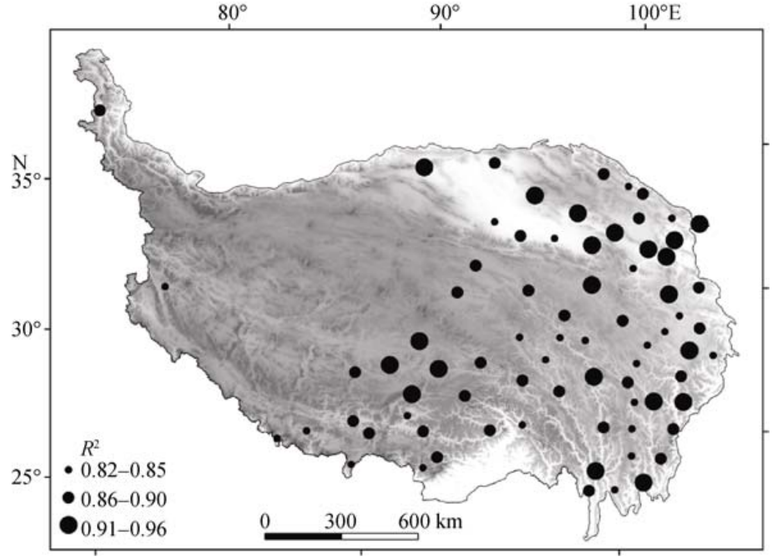

Figure 2 Spatial distribution of correlation coefficient (R^2) between annual E_{pan} and ET_{ref} at the 75 meteorological stations

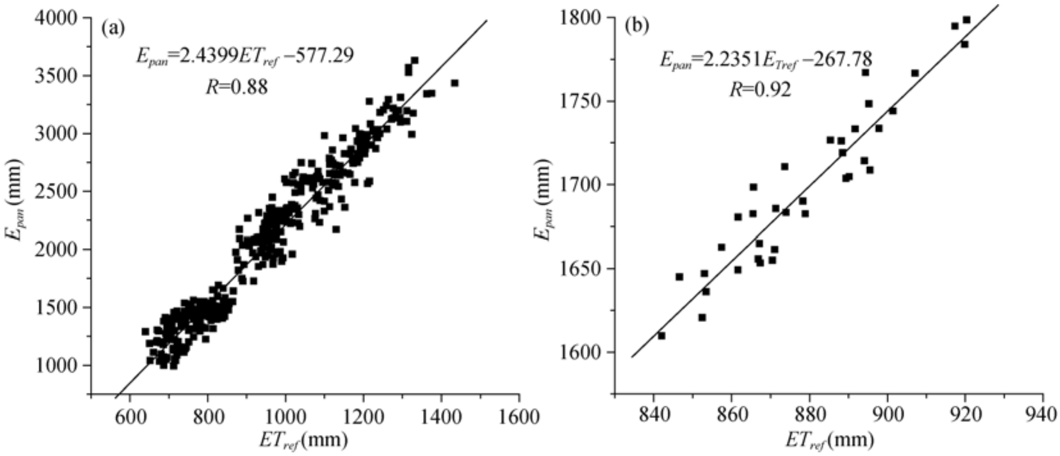

Figure 3 Relationship between annual E_{pan} and ET_{ref} at the 75 meteorological stations (a) and the entire Tibetan Plateau (b) from 1970 to 2005

Table 2 Regression functions between E_{pan} and ET_{ref} for the entire Plateau

Season	Regression equation	R^2
Spring (MAM)	$E_{pan} = 2.857\times ET_{ref} - 227.7$	0.92
Summer (JJA)	$E_{pan} = 2.321\times ET_{ref} - 140.36$	0.94
Autumn (SON)	$E_{pan} = 1.798\times ET_{ref} + 25.6$	0.87
Winter (DJF)	$E_{pan} = 2.495\times ET_{ref} - 68.2$	0.91
Annual	$E_{pan} = 2.235\times ET_{ref} - 267.8$	0.92

the correlation coefficients R^2 between annual E_{pan} and ET_{ref} were all above 0.82 at the 75 stations. Figure 3a shows that R^2 between annual E_{pan} and ET_{ref} of all the 75 stations together was 0.88, while it was 0.92 over the entire Plateau (Figure 3b). Seasonally, the relations between E_{pan} and ET_{ref} can be as high as around 0.90 (Table 2). The good agreement between E_{pan} and ET_{ref} suggests it was reasonable to use Eq.(10) to estimate contributions to the long-term trend in E_{pan}.

4.2 Trends in ET_{ref}, E_{pan} and climate variables

Figure 4 shows long-term trends in annual ET_{ref}, E_{pan} and meteorological variables for the period 1970–2005. It was found that E_{pan} decreased at 49 stations (33 of which showed significant trend), while E_{pan} increased at 26 stations (8 of which with significant trend). In comparison with E_{pan}, the trends of ET_{ref} are almost the same, which implicates again the possibility of using Eq.(10) to estimate the contribution rates. For the entire Tibetan Plateau, the annual ET_{ref} and E_{pan} decreased significantly ($\alpha = 0.05$) from 1970 to 2005 with ET_{ref} decreasing at a rate of 1.41 mm a^{-2} and E_{pan} at 3.06 mm a^{-2} (Figure 5 and Table 3). Seasonally, as shown in Table 3, E_{pan} decreased significantly by 1.10 mm a^{-2}, 1.11 mm a^{-2} and 0.60 mm a^{-2} in spring, summer and autumn, respectively, while the decreasing trend in winter was not significant. Similar to E_{pan}, ET_{ref} decreased significantly by 0.36 mm a^{-2}, 0.50 mm a^{-2} and 0.35 mm a^{-2} respectively in spring, summer and autumn.

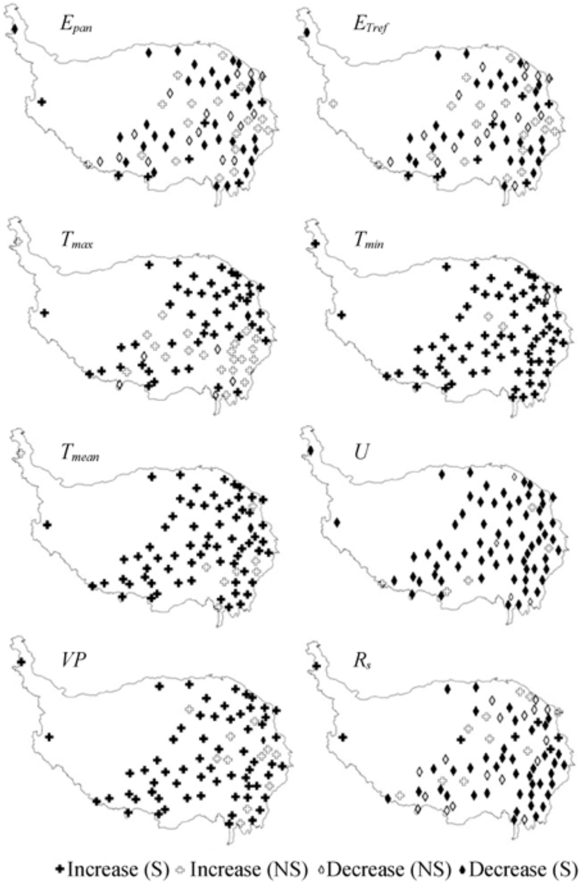

Figure 4 Spatial distributions of trends in annual E_{pan}, ET_{ref} and meteorological variables at 75 stations from 1970 to 2005. Cross symbol indicates an increasing trend (solid cross represents the trend is significant and hollow cross not significant at the level of $\alpha = 0.05$); diamond symbol indicates a decreasing trend (solid diamond represents the trend is significant and hollow diamond not significant at the level of $\alpha = 0.05$).

For the four climate factors concerned, T_{mean} showed significant increasing trends at 66 stations and wind speed showed significant decreasing trends at 66 stations. Vapor pressure and solar radiation decreased significantly at 63 stations and 41 stations, respectively. It is interesting to note that most of the stations where solar radiation decreased significantly are located in the southeastern part of the Plateau, where T_{max} and T_{mean} did not increase as significantly as other parts. Considering the lower elevation and higher population density in the southeastern part, complicated feedback mechanisms may exist between human activities, solar radiation and temperature, which need further researches. For the entire Plateau, Figure 5 and Table 3 show that solar radiation and wind speed decreased significantly by 0.017 MJ $m^{-2}d^{-1}a^{-2}$ and 0.018 $ms^{-1}a^{-2}$, respectively, while vapor pressure increased by 0.0016 kPa a^{-2}. T_{max}, T_{min} and T_{mean} increased by 0.025, 0.041 and 0.031 ℃ a^{-2}, respectively. T_{min} increased more than T_{max} (about 1.6 times), which was also found in other regions of the world (Peterson *et al*., 1995; Roderick and Farquhar, 2002; Xu *et al*., 2006).

4.3 Attribution of pan evaporation trend

Pan evaporation is an integrated effect of climate factors such as solar radiation, temperature,

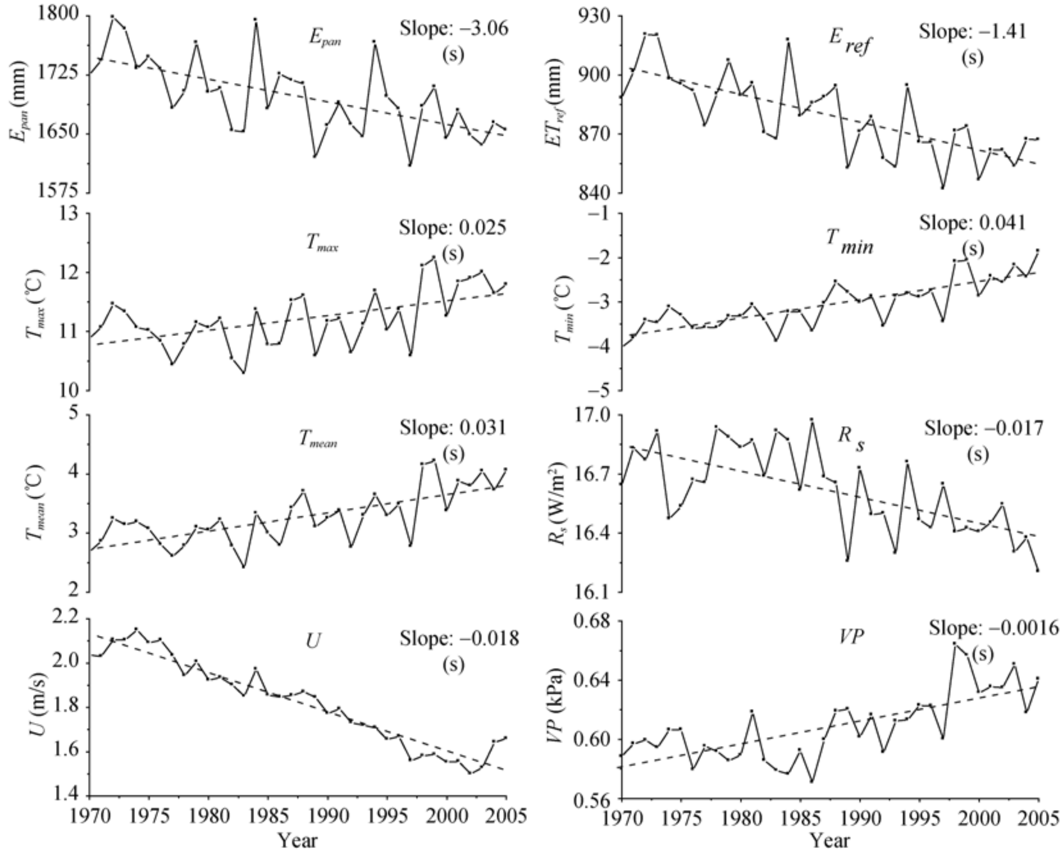

Figure 5 Variation of average annual E_{pan}, ET_{ref} and meteorological variables from 1970 to 2005. Slope represents b in Eq.(1), S represents the trend is significant and NS not significant at the level of $\alpha = 0.05$ by Mann–Kendall test

Table 3 Trend in E_{pan}, ET_{ref} and meteorological variables within the Tibetan Plateau

E_{pan}	Annual	Spring	Summer	Autumn	Winter	
Slope	–3.06	–1.10	–1.11	–0.60	–0.33	
Z	-4.18^*	-2.73^*	-3.12^*	-3.27^*	–1.62	
ET_{ref}	Annual	Spring	Summer	Autumn	Winter	
Slope	–1.41	–0.36	–0.50	–0.35	–0.14	
Z	-3.86^*	-2.36^*	-2.92^*	-3.83^*	–1.47	
Meteorological variables	U	VP	R_s	T_{mean}	T_{max}	T_{min}
Slope	–0.018	0.0016	–0.017	0.031	0.025	0.041
Z	-6.45^*	$+3.67^*$	-4.85^*	$+4.37^*$	$+2.48^*$	$+6.32^*$

Z is the Mann-Kendall test statistic in Eq. (1); ‘*’ means significant trend at the level of $\alpha = 0.05$ by Mann–Kendall test.

vapor pressure, and wind speed. The contribution of change in each climate variable to the long-term trend in ET_{pan} can be quantitatively defined as the product of the partial derivative and the corresponding trend of the climate variable shown in Eq.(10). For the Tibetan Plateau, it can be found that the estimated pan evaporation trends (C_{pan}) using Eq.(10) fit well with that detected from the observed pan evaporation (TR_{pan}) for all the 75 stations (Figure 6). The largest absolute error between seasonal TR_{pan} and C_{pan} was 1.43 mm a^{-2} in summer at station No.56146 with a relative error of –15.1%. Annually, the largest absolute error between TR_{pan} and C_{pan} was 2.76 mm a^{-2} at station No.52825 with a relative error of –21.0%. For the Plateau as a whole, seasonally, Table 4 shows that the absolute errors between TR_{pan} and C_{pan} in spring, summer, autumn and winter were 0.06, –0.01, –0.01 and –0.05 mm a^{-2} with relative errors of –5.45%, 0.90%, 1.67% and 15.15%, respectively. Annually, the absolute error was –0.09 mm a^{-2} with a relative error of 2.94%. In conclusion, the derivation based method used herein well represents the long-term pan evaporation trends in the Tibetan Plateau, which enables the possibility to estimate the contribution rate of each climate factor to pan evaporation changes.

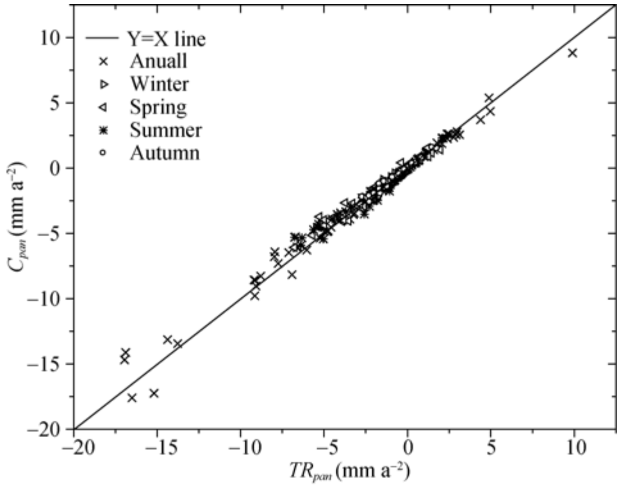

Figure 6 Relationship between the observed pan evaporation trend (C_{pan}) and the calculated pan evaporation trend (TR_{pan}) for different seasons at all the 75 stations from 1970 to 2005

Table 4 Contributions of meteorological variables to the long-term trend in E_{pan}

Period	Contribution					TR_{pan}	ε
	$C'(U)$	$C'(VP)$	$C'(R_S)$	$C'(T_{mzzean})$	C_{pan}		
Spring	-1.20^*	–0.68	–0.05	0.89	–1.04	–1.10	0.06
Summer	–0.66	–0.51	-0.78^*	0.83	–1.12	–1.11	–0.01
Autumn	-0.58^*	–0.34	–0.23	0.54	–0.61	–0.60	–0.01
Winter	–0.36	-0.44^*	–0.04	0.46	–0.38	–0.33	–0.05
Annual	-2.81^*	–1.96	–1.11	2.73	–3.15	–3.06	–0.09
Period	Proportional contribution (%)					$\frac{C_{pan}}{TR_{pan}}$ (%)	$\rho(\varepsilon)$ (%)
	$\rho(U)$	$\rho(VP)$	$\rho(R_S)$	$\rho(T_{mean})$	sum		
Spring	115.38^*	65.38	4.81	–85.58	100.00	94.55	–5.45
Summer	58.93	45.54	69.64^*	–74.11	100.00	100.90	0.90
Autumn	95.08^*	55.74	37.70	–88.52	100.00	101.67	1.67
Winter	94.74	115.79^*	10.53	–121.05	100.00	115.15	15.15
Annual	89.21^*	62.22	35.24	–86.67	100.00	102.94	2.94

Table 4 shows the contributions of each climate variable to the trend in E_{pan}. Annually the increasing T_{mean} should have led to a 2.73 mm a^{-2} increase in E_{pan} and the change in wind speed, vapor pressure and solar radiation should have led to a decrease in E_{pan} at –2.81 mm a^{-2}, –1.96 mm a^{-2} and –1.11 mm a^{-2}, respectively. The combined effects of the four climate variables resulted in a decrease of 3.15 mm a^{-2} in pan evaporation. The proportional contribution rates of mean temperature, vapor pressure, wind speed and solar radiation to the long-term trend in annual E_{pan} were –86.67%, 62.22%, 89.21% and 35.24%, respectively. It is clear that wind speed was the dominant factor for the decrease in E_{pan}, followed by vapor pressure and solar radiation. Temperature, on the contrary, shows an increasing effect of E_{pan}, however, the effect has been offset by changes in vapor pressure, wind speed and solar radiation.

Table 4 also shows the attribution of seasonal E_{pan} trend. In spring, the increased T_{mean} has led to a 0.89 mm a^{-2} increase of E_{pan}, while wind speed, vapor pressure and solar radiation have led to a decrease of E_{pan} at a rate of 1.20 mm a^{-2}, 0.68 mm a^{-2} and 0.05 mm a^{-2}, respectively. The combined effects of the four climate factors resulted in a 1.04 mm a^{-2} decrease in pan evaporation. Among the four factors, wind speed was the dominant factor for the decrease in E_{pan}, followed by vapor pressure and solar radiation. In comparison to spring, the dominant factors of decreasing E_{pan} in summer, autumn and winter are solar radiation, wind speed and vapor pressure respectively. Concurrently, changes in T_{mean} should have led to a 0.83 mm a^{-2}, 0.54 mm a^{-2} and 0.46 mm a^{-2} increase of E_{pan} in summer, autumn and winter.

For different locations of the Tibetan Plateau, as shown in Figure 7, annually, wind speed was the dominant factor for E_{pan} trend at 36 out of 75 stations, accounting for 48.0% of all stations. Temperature was the dominant factor at 26 stations, where pan evaporation increased during the period. Vapor pressure and solar radiation were the dominant factors at 11 and 2 stations, respectively. The results indicate that the increasing temperature indeed should have led to the increase of pan evaporation, but this effect has been offset by the decreasing wind speed and solar radiation and the increasing vapor pressure. Moreover, the decreasing wind speed was the most crucial factor for the decreasing in E_{pan} over the Plateau, followed by vapor pressure and solar radiation.

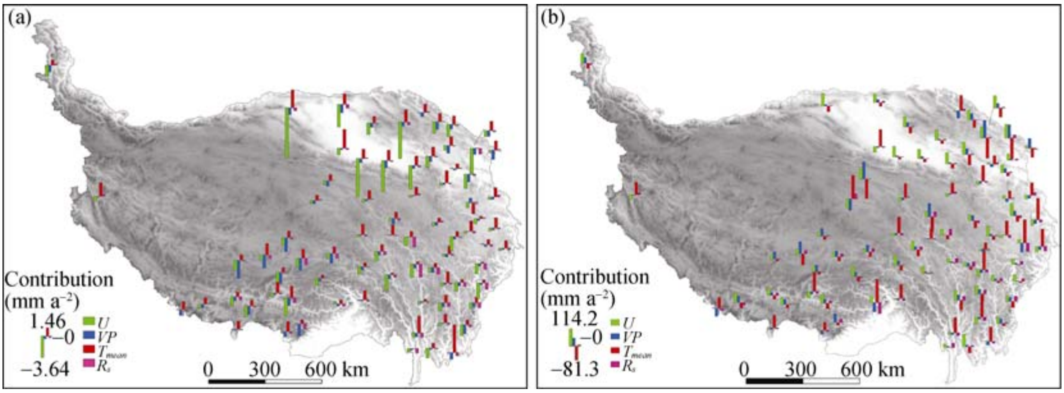

Figure 7 Contributions (a) and proportional contributions (b) of meteorological variables to pan evaporation trends at the 75 meteorological stations from 1970 to 2005

5 Discussion

Evaporation plays an important role in water and energy budget, and decrease in pan evaporation could cause changes in the hydrologic cycle over the Tibetan Plateau. Figure 8 shows the variation of average annual precipitation and aridity index over the Tibetan Plateau, where the aridity index was defined as the ratio between annual potential evapotranspiration and precipitation. It can be seen that annual precipitation increased during the period 1970–2005, while aridity index decreased over the same period (Figure 8). This suggests that the climate became warmer and wetter over the Plateau between the years 1970 to 2005. The decreasing pan evaporation could represent a decline in actual evapotranspiration (Peterson *et al*., 1995). However, it should be noted that actual evapotranspiration is not only controlled by energy (potential evapotranspiration) but also by the water availability, especially in dryer regions. Brutsaert and Parlange (1998) suggested that a decrease in pan evaporation could signal an increase in actual evapotranspiration in non-humid regions according to the Bouchet evaporative complimentary hypothesis (Bouchet, 1963). Though the assumption needs to be further proved and validated (Szilagyi, 2001; Lhomme and Guilioni, 2006; Fu *et al*., 2009), it has been confirmed to be true in the United States (Lawrimore and Peterson 2000; Hobbins *et al*., 2004; Walter *et al*., 2004), Yellow River Basin of China (Liu *et al*., 2006), Australia (Zhang *et al*., 2004) and southeastern Turkey (Ozdogan and Salvucci, 2004). Zhang *et al*. (2007) found that the complementary relationship may exist in the Tibetan Plateau, where actual evapotranspiration increased accompanying with a decreasing potential evapotranspiration from 1966 to 2001. One may also notice that the solar radiation was weakening and wind speed was slowing down (“solar dimming” and “wind stilling”) in the Tibetan Plateau, but the hydrological was accelerating due to increasing precipitation and actual evapotranspiration. It may be because that the increase in greenhouse gas (GHG) concentrations has a significant effect on the energy driving hydrologic cycle (Allen and Ingram, 2002). However, the complex feedbacks between hydrological cycle and GHG radiation forcing need further exploration.

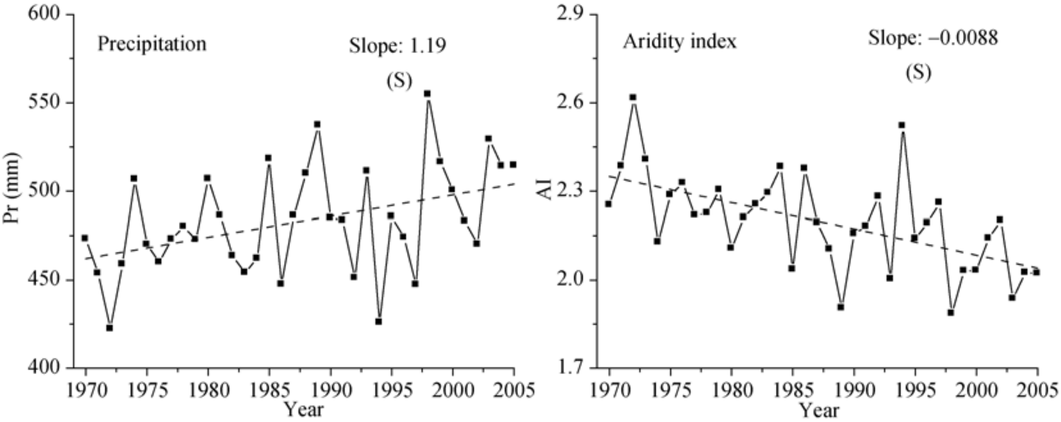

Figure 8 Variation of annual precipitation and aridity index over the Tibetan Plateau

As mentioned above, in addition to temperature, wind speed is an important and dynamic factor for evaporation, and any reduction in wind speed could contribute to decline in pan evaporation. Observed wind speed has decreased over the last years in many regions of the world (Gulev *et al*., 1999; Xu *et al*., 2006; Burn and Hesch, 2007; Roderick *et al*., 2007; Pryor *et al*., 2009; Jiang *et al*., 2010; McVicar *et al*., 2008, 2010). However, the reasons attributed to the change in wind speed have been far less studied than temperature and precipitation. Some researchers interpreted that tall buildings associated with urbanization may cause wind speed reduction (Lam, 2006; Xu *et al*., 2006). This is reasonable, however, anthropogenic impacts within the Tibetan Plateau are far less serious than most regions of the world and the impact of urbanization on wind speed can be assumed to be negligible. Therefore, other reasons must have led to the decrease in observed wind speed in the Tibetan Plateau. The main reason for decrease in surface wind speeds is expected to be due to changes in atmospheric circulation (Pryor *et al*., 2010; Jiang *et al*., 2010). In the context of global warming, the differences of the sea level pressure and near-surface temperature between the Asian continent and the Pacific Ocean are getting significantly smaller and the East Asian trough has shifted eastward and northward and has also weakened (IPCC, 2007). Additionally, East Asian winter and summer monsoons, which strongly control the climate in China, are weakening. The correlation coefficient between the decreasing wind speed in China and the weakening of the winter monsoons and summer monsoons over East Asia is rather high (Jiang *et al*., 2010). The decline of wind speed within the Tibetan Plateau may potentially be due to the changes in global atmospheric circulation.

6 Conclusions

In this study the spatial and temporal variation of pan evaporation (E_{pan}) and related climate variables over the Tibetan Plateau has been detected for the period 1970–2005. It has been found that both annual and seasonal pan evaporation decreased during the period. With the application of the derivation based approach, the contribution rate of wind speed, solar radiation, temperature, and vapor pressure to pan evaporation trend in the Tibetan Plateau has been estimated. The results showed that the increasing temperature indeed should have led to the increase of pan evaporation, but the combined effects of wind speed, solar radiation, and vapor pressure was greater than that of temperature on the change of pan evaporation. In annual scale, the decreasing trend in wind speed was the most crucial factor for the decreasing trend detected in E_{pan} over the Plateau, followed by vapor pressure and solar radiation. In seasonal scale, the decreasing trend in wind speed was the dominant factor for decreasing E_{pan} in spring and autumn, while changes in solar radiation and vapor pressure was the dominant factor in summer and winter, respectively.

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