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Assessing the impact of climate change on potential evapotranspiration in Aksu River Basin

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Abstract: Evapotranspiration is one of the key components of hydrological processes. Assessing the impact of climate factors on evapotranspiration is helpful in understanding the impact of climate change on hydrological processes. In this paper, based on the daily meteorological data from 1960 to 2007 within and around the Aksu River Basin, reference evapotranspiration (RET) was estimated with the FAO Penman-Monteith method. The temporal and spatial variations of RET were analyzed by using ARCGIS and Mann-Kendall method. Multiple Regression Analysis was employed to attribute the effects of the variations of air temperature, solar radiation, relative humidity, vapour pressure and wind speed on RET. The results showed that average annual RET in the eastern plain area of the Aksu River Basin was about 1100 mm, which was nearly twice as much as that in the western mountainous area. The trend of annual RET had significant spatial variability. Annual RET was reduced significantly in the southeastern oasis area and southwestern plain area and increased slightly in the mountain areas. The amplitude of the change of RET reached the highest in summer, contributing most of the annual change of RET. Except in some high elevation areas where relative humidity predominated the change of the RET, the variations of wind velocity predominated the changes of RET almost throughout the basin. Taking Kuqa and Ulugqat stations as an example, the variations of wind velocity accounted for more than 50% of the changes of RET.

Keywords: climate change; reference evapotranspiration; Penman-Monteith method; Aksu River Basin

1 Introduction

Evapotranspiration is one of the key components for energy and water balance of the earth's surface. Changes in climatic elements such as temperature, precipitation, radiation, humidity, and wind speed could have profound implications for hydrologic processes (McKenney and Rosenberg, 1993). In addition to the effects on temporal and spatial variations of runoff

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through the changes of temperature and precipitation, climate change influences evaporation in a high degree (Kundzewicz and Somlyody, 1997). Hulme *et al.* (1994) indicated that global warming could promote the increase of evaporation capacity, while Roderick and Farquhar (2002) found that pan evaporation, an observational and physical representation of potential evaporation (PET), has declined in most parts of the world in the past several decades. According to the supplementary theory, the decrease of actual evapotranspiration will result in the increase of potential evapotranspiration. Chaouche *et al.* (2010) analyzed the change of PET in the context of climate change in a Mediterranean region and found that PET is based not only on temperature but also on relative humidity, solar radiation and wind speed. Documented studies (Peterson *et al.*, 1995; Chattopadhyay and Hulme, 1997; Cohen *et al.*, 2002; Roderick and Farquhar, 2004) showed that different factors influenced the changes of PET in different regions of the world.

About 50 different methods can be used to estimate PET (Lu *et al.*, 2005). Intercomparison of PET methods confirms that Penman-Monteith method is most reliable (Vorosmarty *et al.*, 1998; Lu *et al.*, 2005; Kingston *et al.*, 2009). In the 1990s, Food and Agriculture Organization of United Nations (FAO) recommended Penman-Monteith method, which has a strict definition about the vegetation condition of the surface, as one of the standard methods for calculating Reference Evapotranspiration (RET). RET represents the evaporating power of the atmosphere at a specific location and time and does not consider the crop characteristics and soil factors (Allen *et al.*, 1998).

In China, several studies, focusing on national or regional RET changes, have found that RET changed significantly in most regions of China in the past decades (Gao *et al.*, 2006; Xie and Wang, 2007), except the Loess Plateau region, where the overall trend of RET was not obvious (Wang *et al.*, 2008). RET decreased dramatically in southwest Xinjiang Province and increased observably in the eastern coastal region of China, the middle and upper reaches of the Yellow River Basin and Northeast China (Zhang and Shen *et al.*, 2007; Sun *et al.*, 2009), and declined in various degrees in the North China Plain (Duan *et al.*, 2004; An and Li, 2005; Liu *et al.*, 2010). Different variations of climatic factors have complicated impacts on RET change. The changes of sunshine duration (or net radiation) and saturation deficiency were the factors which mainly aroused the step-changes of RET in China (Zhang and Shen, 2007), while the decline of wind velocity, caused by changes of patterns and intensity of atmospheric circulation, was the main reason of the decrease of RET in the Qinghai-Tibet Plateau (Zhang *et al.*, 2009b) and the diminution of aerodynamic factors was the major cause for the decline of RET in the Tarim River Basin (Han *et al.*, 2009).

The Aksu River Basin, a typical inland basin locating in arid region of northwestern China, having the special landscape pattern with dessert, oasis and river corridor coexisting, is sensitive to climate change (Li *et al.*, 2009). As the Aksu River contributes 73% of the total stream flow of the Tarim River, the Aksu River Basin plays the most important role in ecological and economic systems of the Tarim River Basin (Tan *et al.*, 2004). A large amount of researches (e.g. Wu *et al.*, 2003; Jiang *et al.*, 2005; Chen *et al.*, 2006; Liu *et al.*, 2006; Yang *et al.*, 2006; Zhang, 2007) focused on the impacts of climate changes on the runoff of the Aksu River. However, the above studies are mostly concentrated on the response of river runoff to regional climate change; studies on impacts of climatic factors on evapotranspiration are rarely seen. Due to the complex terrain and the spatial difference of climate factors in the Aksu River Basin, the response of evapotranspiration to climate change would be different over the space. Analyzing and quantifying the impacts of climate changes on evapotranspiration in the Aksu River Basin is essential for assisting policy makers and water resources managers in adopting scientific response strategies for water resources management in arid regions in the context of climate change.

The purpose of this study is to analyze the temporal and spatial changes of RET and quantify the contributions of climate factors to RET variation. To achieve this end, FAO recommended Penman-Monteith method is used to estimate RET based on the data at 9 meteorological stations within and around the Aksu River Basin, and multivariate regression models are employed to quantify the contribution rates of the changes of climate factors to the variation of RET.

2 Methodology

2.1 Study area and data

The Aksu River Basin (Figure 1), with an area of 5.9 × 10^4 km^2, is in the terrain of gradual descent from north to south and from west to east with distinct geomorphological zoning. Vast territory, diverse topography, complex terrain, evident regional climate variations make up characteristics of the northwest mountain climate. The northwest mountain areas have lower temperatures, plentiful precipitation, aged glacier and snow (Ouyang *et al.*, 2007), while southeast plain areas are fairly well in heat conditions with spare rainfall and intense evaporation.

In this study, a dataset, including daily maximum, mean and minimum air temperature ($T_{\max}$, T_a, $T_{\min}$), atmospheric pressure (P), wind velocity (U), mean relative humidity (RH) and sunshine duration (S), at 9 national meteorological stations within and around the Aksu River Basin (Figure 1), is available for the period 1960–2007 from the National Climatic Centre (NCC) of China Meteorological Administration (CMA). These data are used for calculating RET, observing the trends of climate factors and analyzing the impacts of climate factors on RET as well.

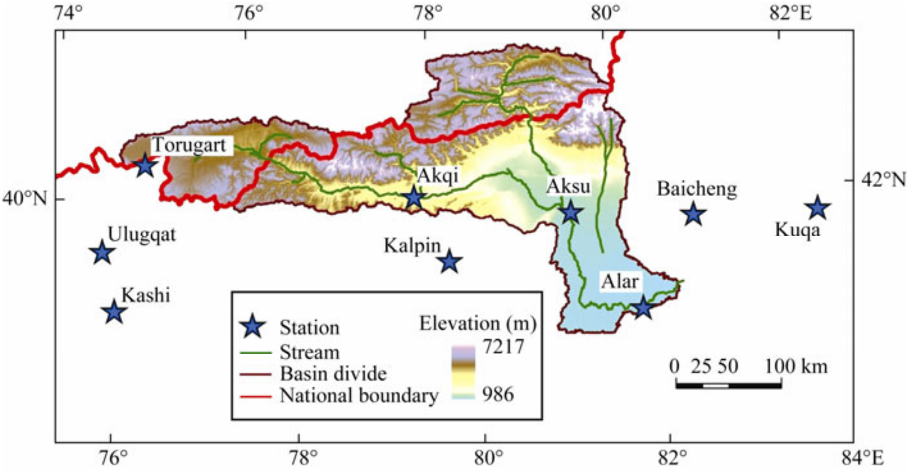

Figure 1 Sketch map of the Aksu River Basin (ARB)

2.2 FAO Penman-Monteith method

According to the FAO definition, the reference surface should closely resemble an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water, 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). FAO Penman-Monteith method expression is as follows:

$$RET = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where RET is reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is mean daily air temperature at 2 m height (℃), u_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), $e_s - e_a$ is saturation vapour pressure deficit (kPa), $\triangle$ is the slope of vapour pressure curve (kPa ℃$^{-1}$), and γ is psychrometric constant (kPa ℃$^{-1}$).

All the above variables can be calculated from daily meteorological observation data. For the calculation of *RET*, wind velocity measured at 2 m above the surface is required. It can be converted from the normal measurement at 10 m wind velocity based on the equation given by the FAO Penman-Monteith method (Allen *et al.*, 1998) as follows:

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \tag{2}$$

where u_2 is the wind velocity at 2 m above ground surface (m s^{-1}), u_z is the measured wind velocity at z m above ground surface (m s^{-1}), and z is the height of measurement above ground surface. Here z = 10 m.

2.3 Trends and changes of climate factors and RET

To analyze the trends and changes of the climate factors and RET, the non-parametric Mann–Kendall test has been applied. Detailed information about Mann–Kendall test can be found in Liu *et al*. (2009a).

2.4 Multivariate regression analysis and relative contribution rate

Multivariate regression analysis is employed to determine the impact of climate change on RET and the contributions of the changes of climate factors to the variation of annual RET. Annual RET was regressed against *T*, *P*, *U*, *RH* and *S* for all the 9 sites. The significance level for an independent variable being added into and removed out from the regression model was 0.05 and 0.1, respectively. In order to estimate the relative contribution rates, before regression analysis, the annual RET and climate factors were standardized based on the expression as follows:

$$X_{ijs} = \frac{X_{ij} - X_{i\min}}{X_{i\max} - X_{i\min}} \tag{3}$$

where X_{ijs} is the standardized value of X_{ij}, $X_{i\max}$ and $X_{i\min}$ are the maximum and minimum value of the sequence of X_i, respectively, j is the jth site. Based on the regression coefficient of each standardized climate factor, the relative contribution rates can be calculated as follows:

$$\begin{cases} Y_s = a_1 X_{1s} + a_2 X_{2s} + a_3 X_{3s} \cdots + a_i X_{is} \cdots \\ \eta_{irelative} = \dfrac{a_i}{a_1 + a_2 + a_3 \cdots + a_i \cdots} \end{cases} \tag{4}$$

where Y_s is the standardized value of RET, X_{is} is the standardized value of climate factors X_i, a_i is the regression coefficient of climate factors X_i, and $\eta_{irelative}$ is the relative contribution rates of change of X_i on the variation of Y.

2.5 Actual contribution rate

According to Mann-Kendall test of annual precipitation and average temperature in the Aksu River Basin over the study period, there were significant upward trends for both of them starting around 1990. Based on the test result, the period of standardized RET and climate factors were divided into two parts: a baseline period (1960–1989) and a changed period (1990–2007). Given the mean values of RET and climate factors in the baseline period and the changed period, the actual changes in RET (ΔY_s) and climate factors (ΔX_{is}) during these two periods could be calculated. And then the actual contribution rates can be calculated as follows:

$$\eta_{iactual} = \frac{a_i \Delta X_{is}}{\Delta Y_s} \tag{5}$$

where ΔY_s and ΔX_{is} are the actual changes of Y_s and X_{is}, respectively, and $\eta_{iactual}$ is the actual contribution rates of change of X_i on the variation of Y.

3 Result and analysis

3.1 Trends of RET in the Aksu River Basin during 1960–2007

The trends of annual mean RET for the period 1960–2007 at 9 sites are shown in Table 1. Strong annual mean RET is found in the eastern plain area while weak annual mean RET is in the western mountainous areas of the basin. The annual mean RET at Kuqa station was 1164.7 mm, which was nearly twice as much as that at Torugart station. In oasis areas, for instance, at Aksu and Alar stations, the annual mean RET was about 1000 mm. RET decreased significantly (hereafter ‘significant’ refers to statistically significant at the 95% confidence level) in most areas in Aksu River Basin, except at Aksu and Ulugqat stations, which had significant increasing trends of RET at the rates of 7.6 and 18.6 mm/10a, respectively. As shown in Table 1, the greatest change of RET happened at Kuqa station, decreasing 51.0 mm/10a. The changes at Baicheng and Torugart were not significant.

The trends of RET in Aksu River Basin were quite different from season to season due to the various climatic conditions in each season (Figure 2). Generally, the change of RET reached the highest in summer (from June to August), which accounted for quite a large proportion of the annual change of RET. The change of RET in spring was larger than that in

Table 1 RET, its trends and the significance at meteorological stations from 1960 to 2007

Year	Kuqa	Baicheng	Alar	Aksu	Kalpin	Akqi	Kashi	Ulugqat	Torugart
1960–1969 (mm)	1307.6	822.5	1091.4	971.3	1114.4	1007.6	1169.1	1043.3	608.1
1970–1979 (mm)	1180.0	846.8	1081.3	963.4	1180.1	1082.7	1177.9	1077.5	638.6
1980–1989 (mm)	1120.1	837.3	1011.5	952.6	1166.6	1001.2	1059.9	1057.4	625.3
1990–1999 (mm)	1078.1	813.6	978.5	970.8	1031.8	899.5	1046.4	1139.8	619.7
2000–2007 (mm)	1130.8	844.7	945.9	1010.4	1000.0	924.1	1188.5	1105.7	613.4
Annual mean (mm)	1164.7	832.5	1024.9	972.2	1102.7	985.5	1125.9	1083.9	621.3
Trend change (mm/10a)	– 51.0	+ 1.0	– 39.9	+ 7.6	– 36.1	– 36.5	– 14.1	+ 18.6	– 0.8
Significance at 95% confidence level	Y	N	Y	Y	Y	Y	Y	Y	N

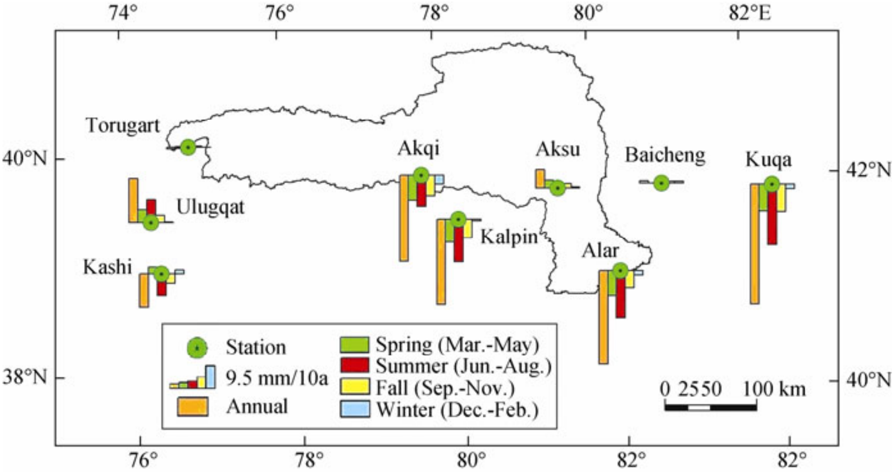

Figure 2 Annual and seasonal trends of RET in ARB

fall, and that in winter was the smallest. Taking Alar station as an example, for the period 1960–2007, the annual change rate of RET was 39.9 mm/10a, while the change in summer is 20.0 mm/10a, which was more than 50% of the annual change. The significant decline in summer RET was coherent with the changes in summer temperature and relative humidity. Because of the cold island effect and wet island effect of oasis, the summer temperature reduced and the relative humidity rose obviously at Alar station in recent decades (Shen *et al*., 2008).

3.2 Impacts of climate factors on RET

Table 2 shows the regression coefficients for climatic factors and the Pearson correlation coefficients (R^2) for the standardized stepwise regression at the 9 sites. The regression simulation effect was well since the average of R^2 was greater than 0.90. *Ta*, *S*, *U* and *RH* were included in almost all the 9 sites' regression models while only 3 sites' regression models included P (Table 2), which indicated that *Ta*, *S*, *U* and *RH* were the universal factors on regional RET variations and *P* just affected some areas' RET in the Aksu River Basin.

The Mann–Kendall test was applied to detect the trends of the annual *Ta*, *S*, *U* and *RH* data over the period 1960–2007 (Table 3). As shown in Table 3, there were significant upward trends in *Ta* and *RH*, downward trends in *U* at most of the sites. All of the stations besides Kuqa showed significant increasing trends in *Ta*, many of which had extremely significant upward trend since their statistically significance is at the 99.9% confidence level. An opposite trend was found in wind speed, which decreased significantly at almost all the 9 sites except Ulugqat, whose wind speed showed a significant increasing trend during the period. In contrast with wind speed, relative humidity increased significantly in all of the stations except Ulugqat and Aksu.

Table 2 Standardized stepwise regression coefficient for climatic factors (*Ta*, *S*, *U*, *RH* and *P*)

Station	Regression coefficient for					R^2
	Ta	*S*	*U*	*RH*	*P*	
Kuqa	0.19	0.31	0.54	–0.30	0.12	0.969
Baicheng	0.51	0.48	0.62	–0.11	0.05	0.827
Alar	0.15	0.34	0.62	–0.15	0.00	0.954
Aksu	0.49	0.34	0.57	–0.23	0.00	0.835
Kalpin	0.00	0.20	0.70	–0.47	0.00	0.888
Akqi	0.16	0.23	0.52	–0.24	0.00	0.958
Kashi	0.20	0.29	0.75	–0.40	0.12	0.938
Ulugqat	0.15	0.21	0.49	–0.41	0.00	0.887
Torugart	0.38	0.19	0.40	–0.61	0.00	0.853

Table 3 The Z value of M-K Trend Test for climatic factors of the meteorological stations

	Kuqa	Baicheng	Alar	Aksu	Kalpin	Akqi	Kashi	Ulugqat	Torugart
T	0.06	4.82^{***}	3.99^{***}	5.92^{***}	2.19^{**}	3.98^{***}	3.57^{***}	2.07^{**}	4.58^{***}
S	–1.04	3.13^{**}	-2.72^{***}	–0.64	–0.02	-3.38^{***}	1.64^{*}	3.27^{***}	–0.14
U	-3.68^{***}	-3.47^{***}	-5.44^{***}	–0.11	-2.9^{***}	-4.89^{***}	-2.31^{**}	4.50^{***}	-2.31^{**}
RH	6.53^{***}	3.00^{***}	6.89^{***}	1.33	4.82^{***}	5.35^{***}	2.54^{**}	–0.16	1.8^{*}

Note: One star (*), two stars (**) and three stars (***) indicate significance at $p < 0.1$, $p < 0.05$ and $p < 0.01$ through the t test, respectively.

At Kuqa station, lying in the eastern plain area of the Aksu River Basin, *U* decreased and *RH* increased significantly, while the other climate factors changed slightly. It indicated that the decline in wind speed and rise in relative humidity were the main causes for the decrease of RET at Kuqa. At Torugart station, locating in the western mountainous area of the Aksu River Basin, *U* decreased and *Ta* increased significantly, *RH* and *S* did not change much. Under the combination of positive impact from increasing *Ta* and the negative impact from decreasing *U*, the reduction of RET at Torugart station was much smaller than that at Kuqa.

Through the above analysis, it is found that change of wind speed is the main cause for the RET variations in the Aksu River Basin. Figure 3 shows the trend of annual mean wind speed from 1960 to 2007 in the basin. It can be seen from Figure 3 that there is an obviously decreasing tendency in annual mean wind speed. And the averaged rate of decrease in annual mean wind speed is about 0.11 m s^{-1} per decade for the study period. The same wind speed change was also detected in the North China Plain (Liu *et al.*, 2009b).

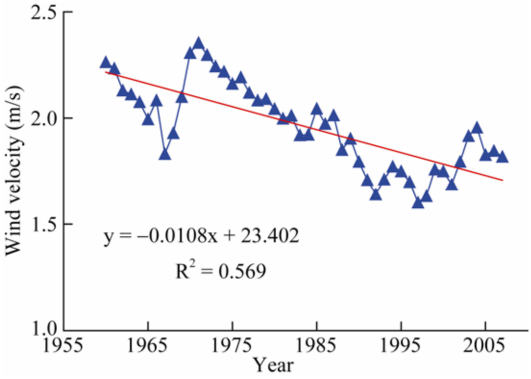

Figure 3 Change of the annual mean wind speed in ARB

It is generally believed that wind speed can be affected mainly by changes in atmospheric factors and ground surface factors, as well as human activities. That the dominant trend of wind speed declines across the Aksu River Basin might originate from the urbanization and the changes of stations' locations and anemometers, and might also be related to the change in large-scale atmospheric circulation (Ren *et al*., 2005; Zhang Aiying *et al*., 2009; Jiang *et al*., 2010). Under the background of global change, the contrasts of the sea level pressure and near-surface temperature between the Asian continent and the Pacific Ocean are getting significantly smaller (IPCC, 2007). As a result of the decline in the contrasts of pressure and temperature between continent and ocean, the circulation would change definitely (Jiang *et al*., 2010). Zhang *et al*. (2009b) and Guo *et al*. (2010) analyzed the changes in geostrophic winds of 500 hPa in Qinghai-Tibet Plateau and 850 hPa in China, respectively, and found that the decrease in surface wind speed corresponded to the decreasing trends of upper-air zonal wind and the decline of pressure gradient. In addition to the urbanization and the changes of measurement environment and large-scale atmospheric circulation, the decline of pressure gradient originating from the increasing in surface temperature (Table 3) might be another important cause of the reduction of wind speed in Aksu River Basin.

3.3 Contribution rates of climate factors on variations of RET

Based on the standardized regression coefficients (Table 2), the relative contribution rate ($\eta_{irelative}$) of each climate factor on RET variation was calculated by Eq. (4). As shown in Figure 4, changes of wind speed had the highest contribution rates to variations of RET at all the 9 sites except Torugart station, at which relative contribution rate of relative humidity was the biggest. The relative contribution rates of the change of wind speed on variations of RET were about 50% at Akqi, Kalpin and Alar, about 40% at Kuqa, Kashi and Ulugqat. In most of the areas, except in the oasis areas (such as Aksu, Baicheng and Alar), the relative contribution rates of relative humidity on variations of RET ranked only second to wind speed. The relative contribution rates of average temperature and radiation duration were relatively smaller than that of wind speed and relative humidity.

The actual contribution rates ($\eta_{iactual}$) of climate factors on variations of RET were calculated by using Eq. (5). Kuqa, Ulugqat and Aksu were taken as examples to analyse the actual contribution rates of climate factors on variations of RET, since the annual change

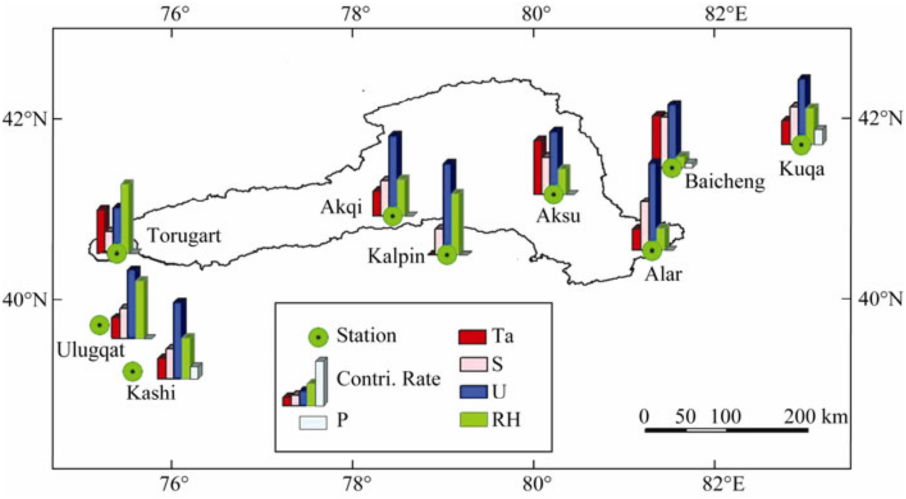

Figure 4 Contribution rates of climatic factors on variations of RET in ARB

rates of RET at the three stations were –51, +18.6 and +7.6 mm/10a (Table 1), respectively, being quite typical.

Table 4 shows the changes in RET and climate factors between 1960–1989 and 1990–2007, and the actual contribution rates of each climate factor on RET variation of Kuqa station. As seen from Table 4, the combined action of the decline in wind speed and pressure, and the increase in relative humidity caused the decline of RET, and each of them had a positive actual contribution rate on the decline of RET. The actual contribution rates of average temperature and radiation duration on the decline of RET were negative since the increase in average temperature and radiation duration retained the decline in RET. The actual contribution rate of wind speed change on the decline of RET was 57.7%, which accounted for more than half of the decline of RET at Kuqa station.

Table 4 Contribution rates of climatic factors on decline of RET at Kuqa

	RET	*Ta*	*S*	*U*	*RH*	*P*
1960–1989	0.49	0.26	0.60	0.55	0.36	0.30
1990–2007	0.27	0.35	0.66	0.31	0.75	0.18
Change	–0.22	0.09	0.06	–0.23	0.38	–0.12
Regression coefficient		0.19	0.31	0.54	–0.3	0.12
Actual contribution rate (%)		–7.8	–8.7	57.7	52.4	6.6

Table 5 Contribution rates of climatic factors on increase of RET at Ulugqat

	RET	*Ta*	*S*	*U*	*RH*
1960–1989	0.29	0.49	0.43	0.33	0.55
1990–2007	0.51	0.61	0.55	0.63	0.48
Change	0.22	0.12	0.13	0.30	–0.07
Regression coefficient		0.15	0.21	0.49	–0.41
Actual contribution rate (%)		8.4	12.1	66.1	12.8

In contrast with Kuqa station, the RET increased in Ulugqat (Table 5). The main cause for the rise of RET in Ulugqat was the rise of wind speed, which accounted for 66.1% of the change in RET. Rise in average temperature and radiation duration, and decline in relative humidity intensified the rise of RET, with the actual contribution rates at 8.4%, 12.1% and 12.8%, respectively.

By comparison, it is easy to find that the RET at both stations, Ulugqat and Aksu, increased significantly, though the trends of wind speed and relative humidity at these two stations were completely contrary. At Aksu station, there was an extremely significant increase of temperature (Table 3), which was the main cause for the rise of RET, accounting for 133% of it (Table 6). While the decrease in wind speed and radiation duration, and increase in relative humidity hindered the rising trend of RET at Aksu station, the summation of the actual contribution rates of them was –33% (Table 6). The positive effect of rise in temperature on the rise of RET was so strong that it offset the negative effect of changes in wind speed, radiation duration and relative humidity on RET. Therefore, the RET at Aksu station rose at a slower speed at 7.6 mm/10a, compared with the trend slope, 18.6 mm/10a, of RET at Ulugqat station.

Table 6 Contribution rates of climatic factors for increase of RET at Aksu

	RET	*Ta*	*S*	*U*	*RH*
1960–1989	0.45	0.34	0.50	0.53	0.63
1990–2007	0.60	0.75	0.50	0.46	0.69
Change	0.15	0.41	–0.01	–0.07	0.05
Regression coefficient		0.49	0.34	0.57	–0.23
Actual contribution rate (%)		133	–1	–25	–8

4 Conclusions

Impact of climate change on potential evapotranspiration is an important aspect of hydrological response to climate change. In this study, the temporal and spatial variation of reference evapotranspiration (RET), which was calculated by using the FAO Penman-Monteith method, has been analyzed, and the effects of the changes of climate factors (e.g. air temperature, solar radiation, relative humidity, vapour pressure and wind speed) on the variation of RET have been differentiated based on the daily meteorological data from 1960 to 2007 within and around the Aksu River Basin.

For the period 1960–2007, the average annual RET in the eastern plain area of the Aksu River Basin was about 1100 mm, which was nearly twice as much as that in the western mountainous area. The trend of annual RET had significant spatial variability. Annual RET decreased significantly in most areas in the Aksu River Basin, except at Aksu and Ulugqat stations, which had significant increasing trends of RET at the rates of 7.6 and 18.6 mm/10a, respectively. The greatest change of RET happened at Kuqa station, decreasing 51.0 mm/10a. The amplitude of the change of RET reached the highest in summer and was the main contributor to the annual change of RET. The change of RET in spring was larger than that in fall, and that in winter was the smallest.

Variations of wind velocity and relative humidity mainly accounted for RET changes in the Aksu River Basin. Except some high elevation areas where relative humidity predominated the changes of the RET, the decline of wind velocity predominated the changes of RET almost throughout the basin. Taking Kuqa and Ulugqat stations as an example, the decline of wind velocity accounted for more than 50% of the changes of RET.

References

Allen R G, Pereira L S, Raes D *et al.*, 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper 56*, *Food and Agriculture Organization of the United Nations*, Rome.

An Yuegai, Li Yuanhua, 2005. Change of evaporation in recent 50 years in Hebei Region. *Journal of Arid Land Resources and Environment*, 19(4): 159–162. (in Chinese)

Chaouche K, Neppel L, Dieulin C *et al.*, 2010. Analyses of precipitation, temperature and evapotranspiration in a French Mediterranean region in the context of climate change. *Comptes Rendus Geoscience*, 342: 234–243.

Chattopadhyay N, Hulme M, 1997. Evaporation and potential evapotranspiration in India under conditions of recent and future climate change. *Agricultural and Forest Meteorology*, 87: 55–73.

Chen Ying, Deng Ziwang, Shi Hongzheng, 2006, Temporal change of annual runoff volume of the Aksu River, a source stream of the Tarim River. *Arid Zone Research*, 23(1): 21–25. (in Chinese)

Cohen S, Ianetz A, Stanhill G, 2002. Evaporative climate changes at BetDagan, Israel, 1964 to 1998. *Agricultural and Forest Meteorology*, 111: 83–91.

Duan Yonghong, Tao Shu, Li Bengang, 2004. Spatial and temporal variation of reference crop evapotranspiration in Beijing. *Chinese Agricultural Meteorology*, 25(2): 22–25. (in Chinese)

Gao Ge, Chen Deliang, Ren Guoyu *et al.*, 2006. Trend of potential evapotranspiration over China during 1956 to 2000. *Geographical Research*, 25(3): 378–387. (in Chinese)

Guo Hua, Xu Ming, Hu Qi, 2010. Changes in near-surface wind speed in China: 1969–2005. *International Journal of Climatology*, doi: 10.1002/joc.2091.

Han Songjun, Hu Heping, Yang Dawen *et al.*, 2009. Differences in changes of potential evaporation in the mountainous and oasis regions of the Tarim Basin, Northwest China. *Science in China* (*Series E*), 52(7): 1981–1989.

Hulme M, Zhao Z C, Jiang T, 1994. Recent and future climate change in East Asia. *International Journal of Climatology*, 14: 637–658.

Intergovernmental Panel on Climate Change, 2007. Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report. In: Solomon S, D.Q, Manning M *et al*. Cambridge, UK: Cambridge University, 996.

Jiang Yan, Zhou Chenghu, Cheng Weiming, 2005. Analysis on runoff supply and variation characteristics of Aksu drainage basin. *Journal of Natural Resources*, 20(1): 27–34. (in Chinese)

Jiang Ying, Luo Yong, Zhao Zongci *et al.*, 2010. Changes in wind speed over China during 1956–2004. *Theoretical and Applied Climatology*, 99: 421–430.

Kingston D G, Todd M C, Taylor R G *et al.*, 2009. Uncertainty in the estimation of potential evapotranspiration under climate change. *Geophysical Research Letters*, 36, L20403, doi: 10.1029/2009GL040267.

Kundzewicz Z W, Somlyody L, 1997. Climatic change impact on water resources in a systems perspective. *Water Resources Management*, 11: 407–435.

Li Hongjun, Jiang Zhihong, Yang Qing, 2009. Association of North Atlantic Oscillations with Aksu River runoff in China. *Journal of Geographical Sciences*, 19(1): 12–24.

Liu Suxia, Mo Xingguo, Zhao Weimin *et al.*, 2009a. Temporal variation of soil moisture over the Wuding River Basin assessed with an eco-hydrological model, in-situ observations and remote sensing. *Hydrology and Earth System Sciences*, 13: 1375–1398.

Liu Suxia, Qiu Jianxiu, Mo Xingguo, 2009b. Wind velocity variation from 1951 to 2006 in the North China Plain. *Resources Science*, 31(9): 1486–1492. (in Chinese)

Liu Xinchun, Yang Qing, Liang Yun, 2006. Study on the change of runoff and the effect factors in the Aksu River

Basin in recent 40 years. *China Population, Resources and Environment*, 16(3): 82–87. (in Chinese)

Liu Yuan, Wang Ying, Yang Xiaoguang, 2010. Trends in reference crop evapotranspiration and possible climatic factors in the North China Plain. *Acta Ecologica Sinica*, 30(4): 923–932. (in Chinese)

Lu J B, Sun G, McNulty S G *et al*., 2005. A comparison of six potential evapotranspiration methods for regional use in the southeastern United States. *Journal of American Water Resources Association*, 41: 621–633, doi: 10.1111/j.1752-1688.2005.tb03759.x.

McKenney M S, and Rosenberg N J, 1993. Sensitivity of some potential evapotranspiration estimation methods to climate change. *Agricultural and Forest Meteorology*, 64: 81–110.

Ouyang Rulin, Cheng Weiming, Wang Weisheng *et al*., 2007. Research on runoff forecast approaches to the Aksu River basin. *Science in China* (*Series D*), 50(suppl.): 16–25.

Peterson T C, Golubev V S, Groisman P Y, 1995. Evaporation losing its strength. *Nature*, 377: 687–688.

Ren Guoyu, Guo Jun, Xu Mingzhi *et al*., 2005. Climate changes of China's mainland over the past half century. *Acta Meteorological Sinica*, 63(6): 942–956. (in Chinese)

Roderick M L, Farquhar G D, 2002. The cause of decreased pan evaporation over the past 50 years. *Science*, 298: 1410–1411.

Roderick M L, Farquhar G D, 2004. Changes in Australian pan evaporation from 1970 to 2002. *International Journal of Climatology*, 24: 1077–1090.

Shen Yongping, Wang Guoya, Zhang Jiangang, 2008. Human activity impacts on local climate and water environments of the Aksu River oasis, South Xinjiang. *Arid Land Geography*, 31(4): 524–534. (in Chinese)

Sun Xiaozhou, Feng Zhiming, Yang Yanzhao, 2009. Change tendency of reference crop evapotranspiration in Xiliaohe Basin. *Resources Science*, 2009, 31(3): 479–484. (in Chinese)

Vorosmarty C J, Federer C A, Schloss A L, 1998. Potential evaporation functions compared on US watersheds: Possible implications for global scale water balance and terrestrial ecosystem modeling. *Journal of Hydrol*ogy, 207(3/4): 147–169.

Wang Youqi, Fan Jun, Shao Mingan *et al*., 2008. Analysis of effects of climate change on reference evapotranspiration on the Loess Plateau in recent 50 years. *Transactions of the CSAE*, 24 (9): 6–10. (in Chinese)

Wu Sufen, Han Ping, Li Yan *et al*., 2003. Predicted variation tendency of the water resources in the headwaters of the Tarim River. *Journal of Glaciology & Geocryology*, 25(6): 708–711. (in Chinese)

Xie Xianqun, Wang Ling, 2007. Changes of potential evaporation in northern China over the past 50 years. *Journal of Natural Resources*, 22(5): 683–691. (in Chinese)

Yang Qing, Sun Churong, Shi Yuguang *et al*., 2006. Estimation of areal precipitation series and its relation to runoff in Aksu River Basin. *Acta Geographica Sinica*, 61(7): 697–704. (in Chinese)

Zhang Aiying, Ren Guoyu, Guo Jun *et al*., 2009a. Change trend analyses on upper-air wind speed over China in past 30 years. *Plateau Meteorology*, 28(3): 680–687. (in Chinese)

Zhang Fangmin, Shen Shuanghe, 2007. Spatial distribution and temporal trend of reference crop evapotranspiration in China. *Journal of Nanjing Institute of Meteorology*, 30(5): 705–709. (in Chinese)

Zhang Guangxing, 2007. The response of annual runoff to the height change at the zero temperature level in summer over Xinjiang. *Acta Geographica Sinica*, 62(3): 279–290. (in Chinese)

Zhang Xueqin, Ren Yu, Yin Zhiyong *et al*., 2009b. Spatial and temporal variation patterns of reference evapotranspiration across the Qinghai-Tibetan Plateau during 1971–2004. *Journal of Geophysical Research,* 114: D15105, doi: 10.1029/2009JD011753.