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ORIGINAL PAPER

Changes in reference evapotranspiration over an agricultural region in the Qinghai-Tibetan plateau, China

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Abstract Reference evapotranspiration (ET_0), as an estimate of the evaporative demand of the atmosphere, has been receiving extensive attention in researches on hydrological cycle. Sensitivity of ET_0 to major climatic variables has significant applications in climatology, hydrology, and agrometeorology and is also important to improve our understanding of the connections between climatic conditions and ET_0 variability. In this study, we used the Penman-Monteith equation to calculate ET_0 and adopted a nondimensional sensitivity coefficient formula to analyze sensitivities of ET_0 to four climatic variables based on daily meteorological data from eight meteorological sites in the Huangshui River basin and surrounding areas during 1961–2010. The results indicated that (1) strong correlations with R^2 up to 0.76 exist between observed E_{pan} and calculated annual ET_0; (2) ET_0 had a decreasing trend in the Huangshui River basin (HRB) during 1961–2010; (3) Spatially, distribution of ET_0 was largely correlated with altitude, for instance, the average annual ET_0 was larger in low-altitude areas than in high-altitude areas; (4) ET_0 was more sensitive to actual vapor pressure in high-altitude areas while it was more sensitive to temperature in low-altitude areas; and (5) ET_0 showed a decreasing trend and was consistent with the decreases in net radiation and wind speed at seasonal and annual time scales in HRB during 1961–2010. Sensitivity analysis of ET_0 to major climatic variables revealed that temperature was primarily responsible for changes in ET_0 in the growing season while actual vapor pressure was the dominating factor causing changes in ET_0 in the nongrowing season. However, annual averaged ET_0 was more sensitive to actual vapor pressure (R^2=0.63), indicating that actual vapor pressure was possibly the primary climatic variable that causes changes in annual ET_0.

1 Introduction

Several large rivers, such as the Yangtze River, Yellow River, Lancang River, Nujiang River, and so on, originate from the Qinghai-Tibetan plateau (QTP) that is regarded as the water tower of Asia. QTP plays a fundamental role in the formation and maintenance of the summer circulation over Asia. It is also the important mechanism influencing the formation of the Asian monsoon (Ruddiman and Kutzbach 1991; An et al. 2001). In recent years, many researches on reference evapotranspiration (ET_0) have reported that global warming had led to changes in the surrounding environment in QTP, including glacial melt accelerating, permafrost ablation accelerating, vegetation degradation increasing, and the number of days of strong wind and sandstorm decreasing (Zhou et al. 2006; Song et al. 2011). Changes of hydrothermal environment will largely influence water yield while the change in energy balance will affect the climate system over QTP (Yin et al. 2008). These changes in the environment will strongly affect the Huangshui River basin (HRB), located in the northeastern part of QTP, a typical agricultural region in this plateau (Fig. 1).

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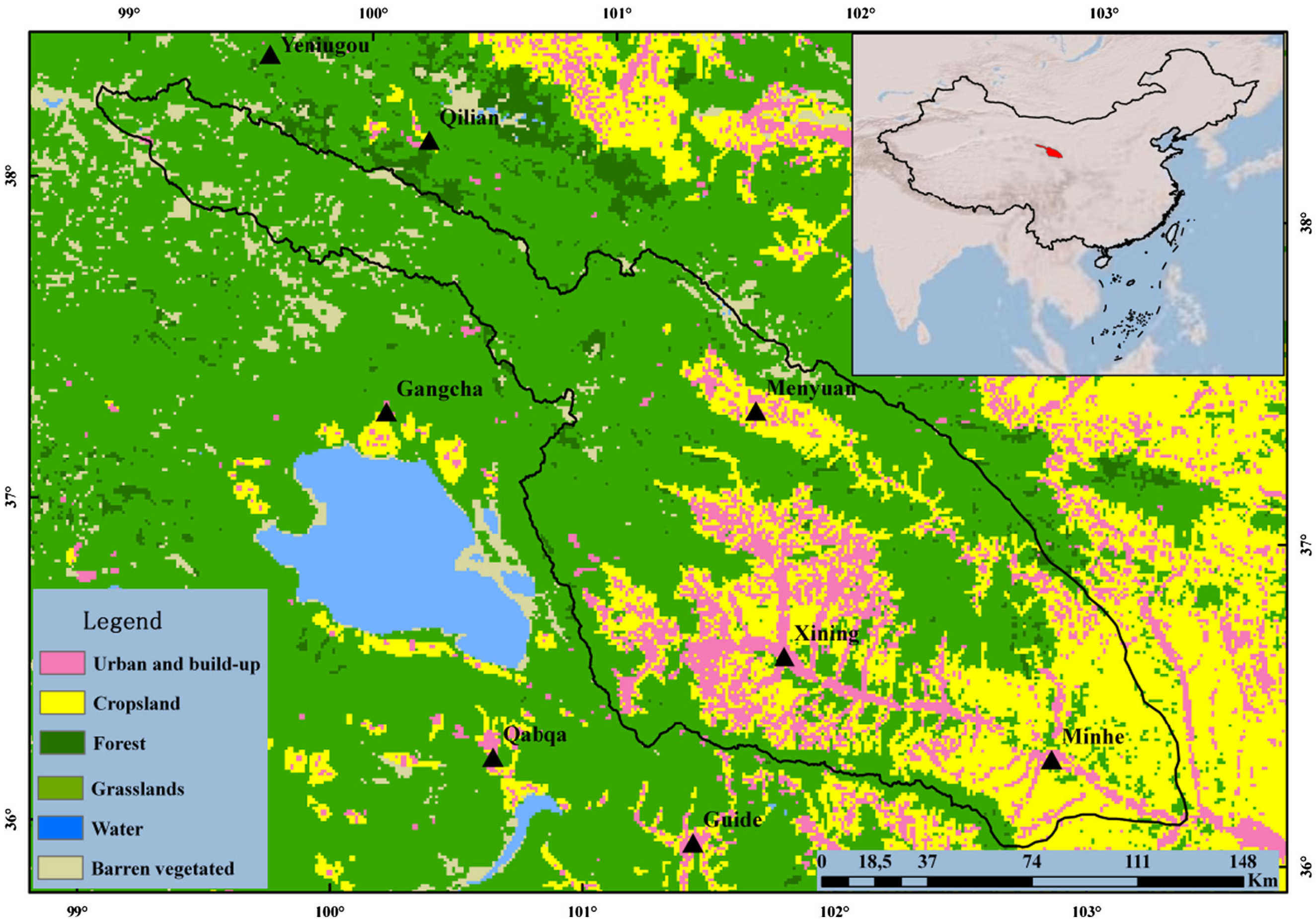

Fig. 1 The location and land use of the Huangshui River basin

Reference evapotranspiration (ET_0), one of the important parameters of the hydrologic cycle, plays a significant role in estimating and predicting actual evapotranspiration, water management, establishing irrigation scheme, and other agricultural production practice. Reference evapotranspiration refers to the evapotranspiration of open grassland under consistent height, vigorous growth, and complete coverage (Allen et al. 1998). ET_0 reflects the impact of atmosphere evaporation capacity on the crop water requirement in different regions and periods, and it is related to climatic variables (Allen et al. 1998). Currently, most studies on pan evaporation and reference evapotranspiration have generally shown a negative trend across the world, such as America (Serrat-Capdevila et al. 2011), Australia (Roderick and Farquhar 2002, 2004; Rotstayn et al. 2006; Roderick et al. 2007, 2009), Spain (Espadafor et al. 2011), Italy (Borin et al. 2011), Siberia (Parka et al. 2008), India (Chattopadhyay and Hulme 1997), China (Thomas 2000; Liu et al. 2010, 2012; Liu and Zhang 2011), Iran (Dinpashoh et al. 2011), and Thailand (Tebakari et al. 2005). For instance, Zhang et al. (2009) found that reference evapotranspiration of QTP has also decreased. Chen et al. (2006) calculated the trend in ET_0 of the Tibetan for the period of 1961–2000 and analyzed responses of ET_0 to climatic perturbations. They also found that ET_0 has a decreasing trend. Many previous researches have also used meteorological data to calculate reference evapotranspiration (ET_0) and analyzed its variation and sensitivity to climatic variables. ET_0 was found to be most sensitive to temperature and relative humidity in the southern Spain located in the southern Europe whose latitude is similar with that of QTP (Estevez et al. 2009). In China, previous studies showed that ET_0 was most sensitive to a number of climatic variables including actual vapor pressure (Liu et al. 2012), relative humidity (Gong et al. 2006), temperature, and net radiation (Liu et al. 2009).

In this study, we will apply the Penman-Monteith formula (Allen et al. 1998) to calculate ET_0 and analyze its sensitivity to several climatic variables. Considering the natural geographical conditions and limited data availability in HRB, this study focused on the spatial and temporal variation of seasonal and annual sensitivity in ET_0 of HRB and surrounding areas during 1961–2010. The analysis of ET_0 variability and its sensitivity at different time scales can improve our understanding of the varying impact of climatic variables on ET_0. Meanwhile, it can also provide a theoretical guidance for the rational development and effective utilization of water resources over HRB in the future.

2 Materials and methods

2.1 Study area and data

The Huangshui River basin (HRB) is located between the longitude 98 and 104° E and the altitude 35 and 39° N and occupying around 38,540 km^2 (Fig. 1). Its topography is complicated, and the elevation varies from 1576 to 5610 m. HRB is one of areas which is often effected by the East Asian Monsoon, South Asian Monsoon, and Plateau Monsoon. The average annual temperature and precipitation vary from 2 to 5 °C and from 241 to 474 mm, respectively. Observed pan evaporation with China 20 cm pan ranges from 1299 to 1752 mm. It is also the area with the densest population, most developed economy, and agriculture over QTP. Studies on the spatial and temporal characteristics of ET$_0$ and sensitivity to main climatic variables in HRB will advance understanding of the climatic and hydrological changes in study area and provide guidance for the agriculture and water resource in the future.

Meteorological data including daily precipitation, air temperature (maximum, minimum, and average), actual vapor pressure, relative humidity, wind speed 10 m above ground, and sunshine hours from eight meteorological sites in HRB and surrounding areas from 1961 to 2010 was obtained from the China Meteorological Administration. Here wind speed 10 m above ground is converted to wind speed 2 m above the ground using the formula recommended by the FAO (Allen et al. 1998).

2.2 Reference evapotranspiration

The Penman-Monteith modified formula (Allen et al. 1998) is as follows:

$$\mathrm{ET}_0=\frac{0.408\Delta(R_n\text{-}G)+\gamma\dfrac{900}{T+273}u_2(e_S\text{-}e_a)}{\Delta+\gamma(1+0.34u_2)} \tag{1}$$

where ET$_0$ is the reference evapotranspiration (mm/day); R_n is the net radiation (MJ/m^2·day); G is the soil heat flux (MJ/m^2·day), is ignored here; γ is the dry and wet constant (kPa/°C); u_2 is the wind speed 2 m above the ground (m/s); e_s is the saturation vapor pressure (kPa); e_a is the actual water vapor pressure (kPa); $\mathrm{e_s-e_a}$ is the saturation vapor pressure deficit (kPa); and Δ is the saturation vapor pressure/temperature curve slope (kPa/°C).

The computation formula of the net radiation (R_n) is as follows (Allen et al. 1998):

$$R_n=R_{ns}\text{-}\,R_{nl} \tag{2}$$

$$R_{ns}=(1\text{-}\alpha)\cdot R_a \tag{3}$$

$$R_{nl}=4.903\times10^{-9}\cdot\left(\frac{(T_{\max}+273)^4+(T_{\min}+273)^4}{2}\cdot(0.34\text{–}0.14\sqrt{e_a})\cdot\left(1.35\cdot\frac{R_s}{R_{so}}\text{–}0.35\right)\right) \tag{4}$$

where R_n is the net radiation, R_{ns} is the shortwave net radiation, R_{nl} is the long-wave net radiation, $T_{\max}$ and $T_{\min}$ are the highest temperature and daily lowest temperature (°C), respectively, e_a is the actual water vapor pressure (KPa), R_a is the extraterrestrial radiation, R_s is the total solar radiation (MJ/m^2), and R_{so} is the sunny radiation (KJ/m^2).

2.3 The nondimensional relative sensitivity coefficients used in this study were calculated following McCuen 1974; Beven 1979

$$SV_i=\lim_{\Delta vi\to0}\left(\frac{\Delta\mathrm{ET}_0/\mathrm{ET}_0}{\Delta V_{\mathrm{i}}/V_{_i}}\right)=\frac{\partial\mathrm{ET}_0}{\partial V_i}\cdot\frac{V_i}{\mathrm{ET}_0} \tag{5}$$

where SV_i represents the sensitivity coefficient of ET$_0$ to climatic variables; in other words, it indicates the fraction of the change in V_i transmitted to ET$_0$ change. V_i represents climatic variables such as air temperature, net radiation, actual vapor pressure, or wind speed. These coefficients are themselves sensitive to the relative magnitudes of ET$_0$ and V_i. Sensitivity coefficients positive or negative of V_i indicate increase or decrease of ET$_0$ with the change in V_i, respectively. Higher coefficients mean higher effects of magnitudes on ET$_0$ estimations. In the past, many researchers have used this methodology to characterize sensitivity models (Saxton 1975; Meyer et al. 1989; Piper 1989; Rana and Katerji 1998) adopting different climatic variables and equations.

2.4 The Mann-Kendall test

The Mann-Kendall method, a nonparametric trend test method, has been commonly used in meteorological and hydrological time series analysis (Yue and Wang, 2002; Zheng et al., 2007). It tests the significance of the sequence mainly through calculating statistics τ and variance σ_t^2 and standardized variables. Related formulas are as follows:

$$M = \tau \big/ \sigma \tag{6}$$

$$\tau = \frac{4S}{N(N-1)} \text{-} 1 \tag{7}$$

$$\sigma_t^2 = \frac{2(2N+5)}{9N(N\text{-}1)} \tag{8}$$

where S is the number of occurrences for all dual sequence of observations (X_i and X_j, $I<j$ in X_i (X_j)) and N is the length of the data set; we use the significance level 0.05; so, the standard normal deviates $|M|>Ma/2=1.96$. If M is positive, it indicates a rising or increasing trend, else it means reducing or decreasing trend.

3 Results

3.1 Seasonal and interannual variations of ET$_0$

Based on the daily meteorological data of the eight meteorological sites in HRB and surrounding areas during 1961–2010, we applied the Penman-Monteith formula to calculate ET$_0$. Figure 2 shows a comparison between calculated ET$_0$ and observed pan evaporation (E_{pan}) from 1960 to 2001. The result revealed that both calculated ET$_0$ and observed E_{pan} had decreasing trends with the agreement of 0.76 (R^2) between them at the eight sites. Therefore, calculated ET$_0$ by the Penman-Monteith can reflect general variation of evapotranspiration in HRB.

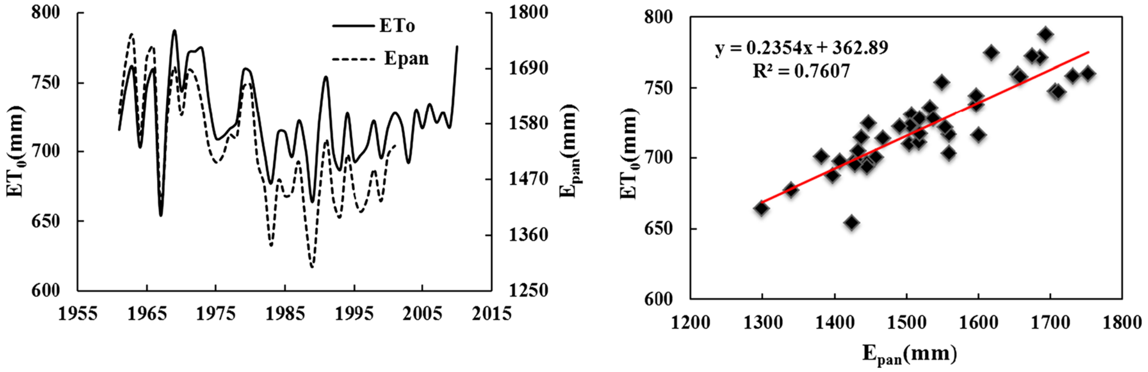

Fig. 2 Comparison of ET$_0$ and E$_{\text{pan}}$ in the study region

The average annual ET$_0$ is 723.8 mm over HRB during 1961–2010 with strong seasonal variation. The maximum value (102.0 mm) occurred in July, and the minimum value (19.0 mm) was in December. Averaged ET$_0$ across the whole HRB had significantly decreased (a=0.05) at −4.9 mm/decade from 1961 to 2010. A change point for ET$_0$ series was identified around the year 2003 with ET$_0$ decreasing from 1961 to 2002 and increasing from 2003 to 2010. (Fig. 3, ET$_0$).

Figure 3 and Table 1 show trends and slope of annual ET$_0$ and climatic variables in HRB. For the whole basin average, both R_n and u decreased significantly from 1961 to 2010 (a= 0.05) at −17.7 MJ·m^{-2}/decade and −0.09 m·s^{-1}/decade, respectively. However, e_a, T, and precipitation (Pr) increased significantly (a=0.05) at 10 Pa/decade, 0.3 °C/decade, and 22.7 mm/decade, respectively. It can be inferred that decreases in R_n and u may be responsible for the decrease in ET$_0$ in HRB during 1961–2010.

3.2 Trends of climatic factors and ET$_0$

Table 1 shows trends of the growing season, nongrowing season, and annual climatic variables in HRB during 1961–2010. As can be seen in Table 1, Pr, T, and e_a increased significantly, while both R_n and u significantly decreased. ET$_0$ was generally decreasing in the three defined periods and had similar trends with R_n and u, suggesting that R_n and u were possibly the primary contributing factors to decreasing ET$_0$. At the seasonal scale, the slope of the nongrowing season ET$_0$ (2.8 mm/decade) is larger than the one of the growing season ET$_0$ (2.1 mm/decade).

Figure 4 shows variation of ET$_0$ in the growing season, nongrowing season, and annual *average* in HRB during 1961–2010. ET$_0$_N (450.3 mm) accounted for 62 % of annual ET$_0$, while ET$_0$_N (273.5 mm) accounted for only 38 %. It

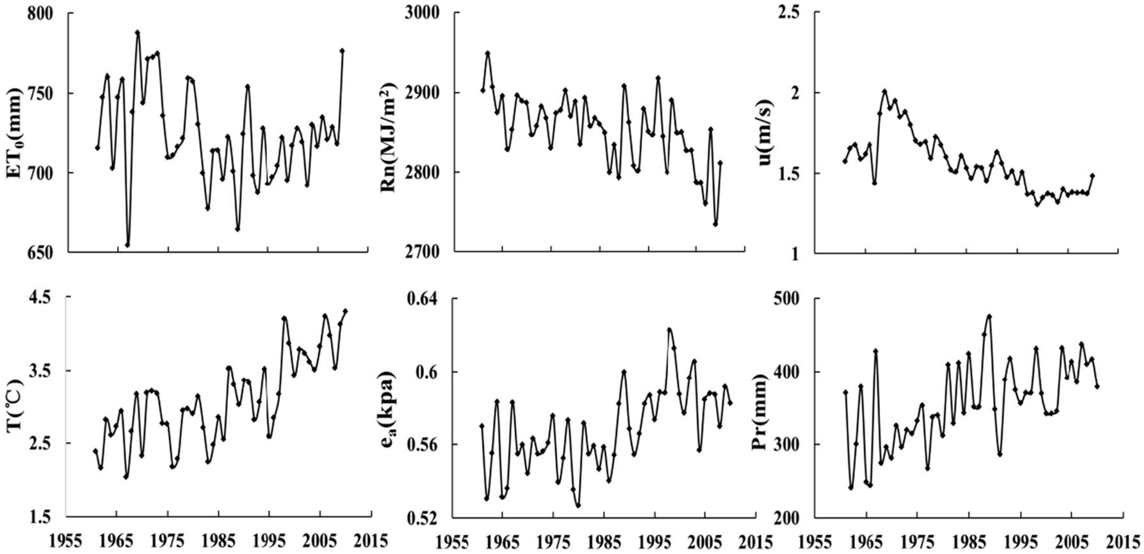

Fig. 3 Trends of annual ET_0 and climatic variables in HRB during 1961–2010

indicates the change in annual ET_0 is primarily influenced by fluctuation of the growing season ET_0. Therefore, in order to more accurately understand the attribution of changing ET_0 at seasonal and annual time scales, we shall adopt sensitivity formula of ET_0 to climatic factors to further analyze reasons of decreases in ET_0 in the next step.

3.3 Sensitivity of ET_0 to climatic variables

Figure 5 shows variation of the growing season, nongrowing season, and annual sensitivity coefficients in HRB during 1961–2010. The growing season, nongrowing season, and annual S (R_n) and S (u) have upward trends; in other words, ET_0 will increase when R_n and u increase. S (e_a) in the growing season, nongrowing season, and annual average has downward trend, namely, ET_0 will decrease with increasing e_a. It also showed that both the growing season and annual S (T) have positive trends, while the nongrowing season S (T) has negative trend. It indicates growing season and annual ET_0 will increase with increases in T, while the nongrowing season ET_0 will decrease with decreases in T.

In general, a positive/negative sensitivity coefficient of certain climatic variable indicates that ET_0 will increase/decrease with the increases in climatic variable. The larger the sensitivity coefficient, the stronger influence certain climatic variable has on ET_0. T is the most sensitive climatic variable (S (T)=1.40), which indicates T has the largest effect on ET_0 during the growing season (Fig. 5a). e_a is the most sensitive variable (S (e_a)=0.64), which reveals e_a has larger effect on ET_0 during the nongrowing season. It is similar with the nongrowing season that annual e_a is the most sensitive variable (S (e_a)=0.63), followed by R_n (S (R_n)=0.52), u (S (u)=0.35), and T is the most insensitive variable (S (T)=0.33) (Fig. 5c). Further, S (T) varied from −1.2 to 2.2, indicating the sensitivity of ET_0 to T is the most unsteady. Meanwhile, other climatic variables are relatively steady.

3.4 Spatial changes of ET_0 and sensitivity coefficients

Table 2 shows trends of the growing season, nongrowing season, and annual ET_0 and sensitivity coefficients in HRB during 1961–2010. There are different trends in ET_0 and sensitivity coefficients during the growing season, nongrowing season, and annual scale. Growing season ET_0 has an increasing trend in high-altitude areas while it has a downward trend in low-altitude areas. Both the nongrowing season and annual scale ET_0 have downward trends in the lower regions of HRB, especially Xingning and Minhe sites.

In growing season, both S (R_n) and S (u) have positive significant trends in most regions, while trend of S (T) is not

Table 1 Trends of the major climatic variables in the growing season, nongrowing season, and annual bases during 1961–2010

	Precipitation (mm/decade)	Temperature (°C/decade)	Wind speed ($m \cdot s^{-1}$/decade)	Net radiation ($MJ \cdot m^{-2}$/decade)	Actual vapor pressure (Pa/decade)	ET_0 (mm/decade)
Growing season	13.4[a]	0.25[a]	−0.1[a]	−11.2[a]	12[a]	−2.1
Nongrowing season	9.3[a]	0.35[a]	−0.09[a]	−6.5[a]	7[a]	−2.8
Annual	22.7[a]	0.3[a]	−0.09[a]	−17.7[a]	9[a]	−4.9

[a] Indicates significance at 0.05 confidence level

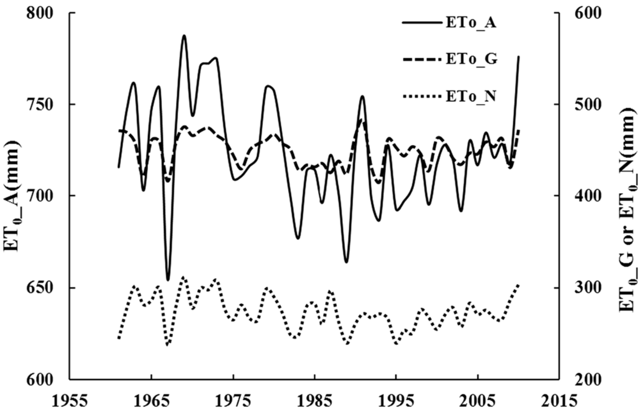

Fig. 4 Variations of the growing season, nongrowing season, and annual ET_0 in HRB during 1961–2010 (*ET_0_A* annual ET_0, *ET_0_G* growing season ET_0, *ET_0_N* nongrowing season ET_0)

significant in all regions. S (e_a) shows a significantly positive trend except for Yeniugou site. In the nongrowing season, ET_0 shows positive trends in Qabqa and Qilian areas and has negative trends in other sites, especially ET_0 has significantly negative trends in Xining and Minhe sites. S (R_n) shows positive trends while S (T) still has no trend, and S (e_a) has a positive trend, except for Qilian and Guide sites while S (u) varied largely. Annual ET_0 shows a positive trend in the high-altitude areas and a negative trend in the low-altitude areas. S (R_n) shows a positive trend except for Qilian site while S (e_a) shows a positive trend except for Yeniugou site; S (T) shows a positive trend except for Qabqa site while S (u) varies largely.

Table 3 shows the mean growing season, nongrowing season, and annual ET_0 and sensitivity coefficients over HRB during 1961–2010. Spatially, ET_0 is higher in lower elevation in HRB at seasonal and annual time scales. For instance, average annual ET_0 (584.4 mm) in Yeniugou site located in high-altitude areas is less than ET_0 (864.5 mm) in the Guide site located in lower-altitude areas.

In the growing season, T is the most sensitive variable among the four climatic variables. It indicates T is a main contributing climatic factor causing change in ET_0. S (T) increases from 0.94 (Gangcha site) to 2.18 (Minhe site) with the decrease in elevation. In the nongrowing season, e_a is the most sensitive variable, which reveals e_a is the main controlling climatic factor causing change in ET_0. Both S (e_a) and S (u) decrease with the decrease in altitude while S (R_n) increases inversely with altitude. Annual e_a is the most sensitive variable, indicating e_a is the dominating climatic factor causing change in ET_0. Both S (T) and S (R_n) increase in lower altitudes.

In a word, actual vapor press is the primarily influencing climatic variable causing change in ET_0, which is inconsistent with the above result that ET_0 decrease was caused by decreases in net radiation and wind speed. Therefore, trend analysis along cannot entirely explain changing ET_0; a more quantitative sensitivity analysis method is necessary to analyze attribution of changing ET_0.

4 Discussions

Sensitivity analysis can help understand influence of different climatic variables on ET_0. In this study, the nondimensional sensitivity coefficient was used to analyze responses of ET_0 to perturbations of four climatic variables in the HRB basin. ET_0 is calculated with the FAO-56 Penman-Monteith formula. The analysis was based on meteorological data set of daily air temperature, wind speed, relative humidity, and daily sunshine duration at eight meteorological observatory stations from 1961 to 2010. Due to the fact that complexity of topography and mutability of climate would lead to changes in climatic variables and evapotranspiration, this study only investigated the impact of climatic variables on ET_0 and focused on spatial and temporal variation and attribution of changing ET_0. Though the trends and sensitivity of climatic variables can reflect the reason of changing ET_0, we found that trends of ET_0 and its influencing climatic factors are different at seasonal and annual time scales. There are possible contributors to the change in ET_0 that are not climatic

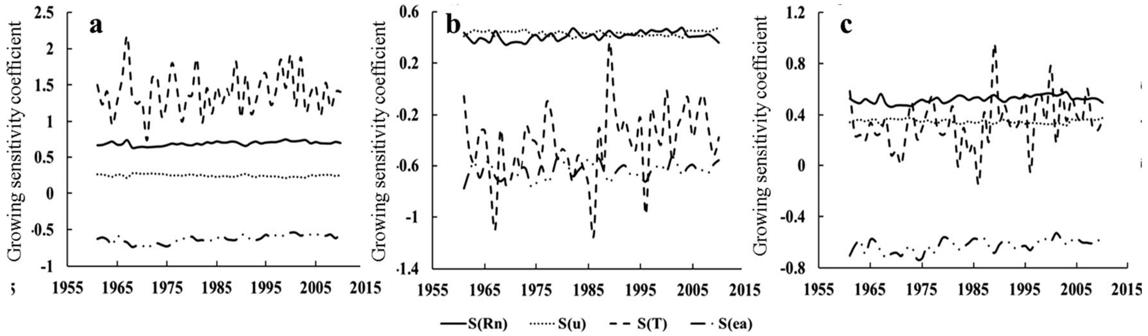

Fig. 5 Variations of the growing season, nongrowing season, and annual sensitivity coefficients of the different variables in HRB during 1961–2010. (S (Rn), S (u), S (T), and S (e_a) indicate the sensitivity coefficients for net radiation, wind speed, temperature, and actual vapor press, respectively)

Table 2 Trends of average in the growing season, nongrowing season, and annual ET_0 and sensitivity coefficients over HRB during 1961–2010

		Gangcha	Yeniugou	Menyuan	Qabqa	Qilian	Xining	Guide	Minhe
	Elevation (m)	3306	3225	2877	2835	2724	2256	2246	1815
Growing season (/decade)	ET_0 (mm/decade)	2.82	2.08	0.50	4.52	2.68	−16.88[a]	−5.08	−7.34
	$S(R_n)$	0.003	0.002[a]	0.013[a]	0.003	0	0.038[a]	0.015[a]	0.011
	$S(e_a)$	0.02[a]	−0.01	0.04[a]	0.02[a]	0.01[a]	0.07[a]	0.03[a]	0.02
	$S(T)$	0.06	−0.01	0.04	−0.09	−0.01	−0.01	0.06	0.08
	$S(u_2)$	0.001	0.002	0.007[a]	0.005	0.003	0.006[a]	0.006[a]	0.008
Nongrowing season (/decade)	ET_0 (mm/decade)	−0.30	−0.10	−4.53	3.70	1.93	−13.57[a]	−3.09	−7.02[a]
	$S(R_n)$	0.006[a]	0.001	0.002[a]	0.005	0.001	0.004[a]	0.003	0.001[a]
	$S(e_a)$	0.01	0.02	0.03[a]	0.02[a]	−0.002	0.06[a]	−0.02[a]	0.01
	$S(T)$	0.02	0.12	0.05	0.01	0.13	0.06	0.04	0.03
	$S(u_2)$	0.006[a]	0.001	−0.007[a]	0.001	0.004[a]	−0.014[a]	0.010[a]	−0.003
Annual (/decade)	ET_0 (mm/decade)	4.61	1.98	−4.03	8.22	2.52	−30.44[a]	−8.17	−14.36[a]
	$S(R_n)$	0.005[a]	0.002	0.002[a]	0.004	−0.009	0.004[a]	0.004	0.001[a]
	$S(e_a)$	0.01	−0.01	0.03[a]	0.02[a]	0.01	0.06[a]	0.001	0.002
	$S(T)$	0.04	0.06	0.04	−0.04	0.07	0.03	0.05	0.05
	$S(u_2)$	0.004	0.001	−0.007[a]	0.001	0.003	−0.019[a]	0.003	−0.004

[a] Indicates significance at 0.05 confidence level

variables. For instance, vegetation coverage, soil moisture, topography, land-use change and human activities, and so on can also change ET_0 to different degrees. In order to better understand reasons for the decreasing ET_0, it requires further investigation by other more efficient methods. This result will provide a theoretical guidance for the rational allocation and management of water resources and lay the foundation for the study of crop water requirement of HRB in the future.

5 Conclusions

We adopted the Penman-Monteith formula (recommended by FAO) to calculate ET_0 and used the Mann-Kendall trend tests to analysis temporal and spatial variation of ET_0 and its sensitivity to major climatic variables in HRB. The daily meteorological data of eight meteorological sites in the Huangshui River basin from 1961 to 2010 was used in this study. The results show that (1) the R^2 between measured and

Table 3 Mean growing season, nongrowing season, and annual ET_0 and sensitivity coefficients over HRB during 1961–2010

		Gangcha	Yeniugou	Menyuan	Qabqa	Qilian	Xining	Guide	Minhe
Elevation (m)		3306	3225	2877	2835	2724	2256	2246	1815
Growing season	ET_0 (mm)	417.0	361.0	374.4	488.6	440.8	475.3	534.6	510.6
	$S(R_n)$	0.59	0.66	0.76	0.69	0.68	0.76	0.7	0.75
	$S(e_a)$	−0.91	−0.84	−0.68	−0.51	−0.61	−0.49	−0.52	−0.47
	$S(T)$	0.94	0.73	0.98	1.41	1.34	1.68	1.92	2.18
	$S(u_2)$	0.29	0.26	0.2	0.26	0.26	0.22	0.25	0.22
Nongrowing season	ET_0 (mm)	301.0	223.4	217.7	297.4	246.3	270.0	330.0	302.6
	$S(R_n)$	0.26	0.31	0.47	0.44	0.38	0.49	0.46	0.47
	$S(e_a)$	−0.74	−0.83	−0.71	−0.47	−0.6	−0.6	−0.5	−0.67
	$S(T)$	−0.5	−0.38	−0.76	−0.51	−0.61	−0.25	−0.3	−0.03
	$S(u_2)$	0.45	0.46	0.41	0.43	0.48	0.4	0.41	0.42
Annual	ET_0 (mm)	687.1	584.4	592.1	786.0	718.0	745.3	864.5	813.2
	$S(R_n)$	0.39	0.45	0.59	0.53	0.49	0.6	0.55	0.58
	$S(e_a)$	−0.8	−0.82	−0.69	−0.48	−0.59	−0.55	−0.5	−0.58
	$S(T)$	0.1	0.08	−0.03	0.29	0.2	0.54	0.61	0.88
	$S(u_2)$	0.38	0.37	0.32	0.36	0.38	0.32	0.34	0.33

modeled annual mean ET_0 reached up to 0.76 at all eight sites during 1961–2001. The average annual ET_0 of HRB was 723.8 mm, and ET_0 had a decreasing trend in HRB during 1961–2010. The decreasing trend of ET_0 was similar to the trends in net radiation and wind speed and was in contrary to the increasing trend in actual vapor pressure and temperature. (2) Spatially, distribution of ET_0 was highly correlated with altitude. For instance, the average annual ET_0 in low-altitude areas was larger than that in high-altitude areas. ET_0 was more sensitive to the actual vapor pressure in high-altitude areas while it was more sensitive to temperature in low-altitude areas. (3) At seasonal and annual time scales, ET_0 showed a decreasing trend that was consistent with the decreases in net radiation and wind speed in HRB during 1961–2010. ET_0 was more sensitive to temperature (with sensitivity coefficient 1.40) in the growing season and was more sensitive to actual vapor pressure (0.64) in the nongrowing season. These results indicate that temperature is the primary contributing climatic factor to changing ET_0 in the growing season while in the nongrowing season actual vapor press is the control climatic factor. Nevertheless, annual ET_0 was more sensitive to actual vapor pressure (0.63), followed by net radiation (0.52), wind speed (0.35), and temperature (0.33). Sensitivity of ET_0 to temperature was unstable at seasonal and annual time scales in HRB during 1961–2010. For the whole HRB, the actual vapor pressure is the dominant influencing factor of changing ET_0.

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