

# Temporal variations of reference evapotranspiration and its sensitivity to meteorological factors in Heihe River Basin, China

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## Abstract

On the basis of daily meteorological data from 15 meteorological stations in the Heihe River Basin (HRB) during the period from 1959 to 2012, long-term trends of reference evapotranspiration ( $ET_0$ ) and key meteorological factors that affect  $ET_0$  were analyzed using the Mann-Kendall test. The evaporation paradox was also investigated at 15 meteorological stations. In order to explore the contribution of key meteorological factors to the temporal variation of  $ET_0$ , a sensitivity coefficient method was employed in this study. The results show that: (1) mean annual air temperature significantly increased at all 15 meteorological stations, while the mean annual  $ET_0$  decreased at most of sites; (2) the evaporation paradox did exist in the HRB, while the evaporation paradox was not continuous in space and time; and (3) relative humidity was the most sensitive meteorological factor with regard to the temporal variation of  $ET_0$  in the HRB, followed by wind speed, air temperature, and solar radiation. Air temperature and solar radiation contributed most to the temporal variation of  $ET_0$  in the upper reaches; solar radiation and wind speed were the determining factors for the temporal variation of  $ET_0$  in the middle-lower reaches.

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**Keywords:** Reference evapotranspiration; Evaporation paradox; Meteorological factor; Heihe River Basin

## 1. Introduction

Evapotranspiration plays an important role in the hydrological cycle as well as the global energy budget. It contributes 2/3 of annual precipitation and has an essential influence on the Earth's climate system (Jayawardena, 1989; Chahine, 1992; Zhan et al., 2011; Zuo et al., 2012; Duhan et al., 2013). In addition, evapotranspiration is a key input to hydrological models (Liang et al., 1994; Gerten et al., 2004; Zhao et al., 2013). Therefore, a comprehensive understanding of temporal trends and spatial distribution of evapotranspiration is highly

significant to water resource management, especially in places where the water availability is limited.

Global warming has been one of the most concerning issues for governments. As reported in the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC), the surface temperature of the Earth has increased by about 0.13 °C per decade over the past 50 years (IPCC, 2007). This has significant impacts on environmental systems, by causing glaciers to melt, the sea level to rise, etc. Global warming also breaks the balance of eco-systems and threatens food supplies. Some studies on climate change have predicted that one of the phenomena that global warming will bring about is an increase in the rate of evaporation from terrestrial open water bodies, which will enhance the scarcity of water resources in arid regions (Jackson, 2001; Scheffer et al., 2001; Yang et al., 2009; Jayantha et al., 2011; Sjoegersten, 2013).

Observed pan evaporation data have revealed the fact that evaporation from open water bodies has been decreasing over the past several decades in different regions around the world

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(Brutsaert et al., 1998; Gao et al., 2012; Yesihrmak, 2013), including Australia (Roderick and Farquhar, 2004), Canada (Aziz and Burn, 2006), Eurasia (Velichko et al., 2008), China (Cong et al., 2009), and India (Rao and Wani, 2011). The contrast between the increase in air temperature and the decrease in observed pan evaporation rate is referred to as the evaporation paradox (Roderick and Farquhar, 2002). Furthermore, a similar decreasing trend of reference evapotranspiration ( $ET_0$ ) was also found by Thomas (2000) and Roderick and Farquhar (2004).

In order to investigate the evaporation paradox, many studies have been carried out. Generally, these studies can be divided into two categories. One includes studies meant to determine the key factors that impact pan evaporation and  $ET_0$  and analyze variations of these key factors so as to explain the reason why pan evaporation and  $ET_0$  have decreased over the past several decades. The other includes studies that focus on determining whether decreasing pan evaporation or  $ET_0$  definitely leads to the decrease in actual evapotranspiration. Studies concerning spatial and temporal variations in pan evaporation and  $ET_0$  have been carried out by researchers worldwide. Gao et al. (2006) studied spatial and temporal variations in  $ET_0$  at 580 stations in China during the period from 1956 to 2000, and, through a partial correlation analysis, the study determined that sunshine duration, wind speed, and relative humidity have a significant impact on  $ET_0$ . Wang et al. (2014) analyzed the relationship between the variations of  $ET_0$  and each climatic variable at Linhe Station, a representative weather station in the Hetao Irrigation District of China, during the period from 1954 to 2012. The results showed that  $ET_0$  in the Hetao Irrigation District is most sensitive to mean daily air temperature, followed by wind speed. Changes in sunshine duration had only a minor effect on  $ET_0$  during the study period. Recent analysis from Wang et al. (2012) indicated that the aerodynamic component of  $ET_0$  accounted for 86% of the long-term changes in global  $ET_0$  from 1973 to 2008. However, Matsoukas et al. (2011) showed the opposite conclusion: trends in  $ET_0$  more closely followed trends in energy availability than trends in atmospheric holding capability for vapor transfer.

These studies have come to quite different conclusions in different regions, indicating a need for new methods to identify the most important meteorological factors in explaining changes in  $ET_0$  at the regional level. Besides, most of these studies focused on the theoretical sensitivity of  $ET_0$ , which is the expected variation of  $ET_0$  due to changes in variables under the assumption that only one variable changes while other variables remain the same. In fact, the theoretical sensitivity of  $ET_0$  does not consider the actual changes in meteorological variables. However, the explanation of meteorological factors controlling changes in  $ET_0$  must consider both the sensitivity of and long-term changes in the meteorological factors themselves.

In this study, overall analysis of the variation of  $ET_0$  in the arid region in northwestern China was carried out. The study mainly focused on both the temporal trends of annual and

seasonal  $ET_0$  and quantitative analysis of the contributions of different meteorological variables to the variation of  $ET_0$ . The objectives of this study included: (1) to detect the long-term trends in  $ET_0$  and air temperature using the Mann-Kendall (M-K) test; (2) to investigate the evaporation paradox at 15 stations by comparing the changing trends in annual  $ET_0$  with the changing trends in air temperature, in order to compensate for the lack of pan evaporation data in the Heihe River Basin (HRB), because Zuo et al. (2010) found a linear relationship between pan evaporation and  $ET_0$  in northwestern China and a coefficient of determination greater than 0.97, verifying the rationality of using the variation of  $ET_0$  to reflect the variation of pan evaporation in this study; and (3) to quantify the contribution of key meteorological factors (air temperature, solar radiation, relative humidity, and wind speed) to the variation of  $ET_0$  and explain the reason for the evaporation paradox using the sensitivity coefficient method.

## 2. Study area and data

### 2.1. Study area

The HRB, covering an area of approximately 134 000 km<sup>2</sup>, is the second largest inland river basin in northwestern China and spans Qinghai and Gansu provinces as well as the Inner Mongolia Autonomous Region from upper reaches to lower reaches. The HRB is located between latitude 37.50°N and 42.40°N, and longitude 98°E and 102°E (Fig. 1).

The HRB is situated in the interior of the Eurasian continent and dominated by arid hydrological characteristics with a mean annual precipitation of approximately 400 mm and a mean annual  $ET_0$  of approximately 1 600 mm. The precipitation, temperature, evaporation, and runoff in the HRB vary greatly at both spatial and temporal scales. The dominant land use types are desert land and grass land, occupying approximately 60% and 25% of the total area, respectively. Due to its important role in water resources management in northwestern China, the HRB has long been a focus of studies on inland rivers in arid regions.

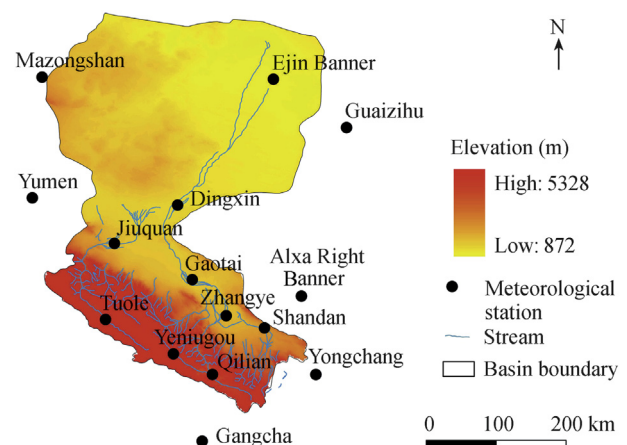


Fig. 1. Meteorological stations in and around HRB.

## 2.2. Data

Six daily meteorological variables (observed daily mean, maximum and minimum air temperatures, relative humidity, wind speed at the height of 2 m, and sunshine duration) derived from the ground surface climatic data sets at 15 national meteorological stations from 1959 to 2012 (Fig. 1) in and around the HRB were obtained from the Environmental and Ecological Science Data Center for West China. The six variables were used as input data for the FAO56 Penman-Monteith (FAO56 P-M) method to estimate daily values of  $ET_0$ . The autocorrelation method was employed in this study to analyze the persistence, which is the tendency for successive values of a meteorological data series to remember the antecedent values (Giles and Flocas, 1984). The results reveal that, for all 15 stations in the HRB, autocorrelation coefficients of annual and seasonal air temperatures and  $ET_0$  series are quite low, which means a low persistence in the data series.

## 3. Methods

### 3.1. FAO56 P-M method

The FAO56 P-M method, which is considered the most accurate method to estimate  $ET_0$  under different climatic conditions, was employed to estimate the daily values of  $ET_0$  in this study. Monthly and annual values of  $ET_0$  were obtained by adding up the daily values. The equation of the FAO56 P-M method (Allen et al., 1998) is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma[900/(T + 273)]u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where  $ET_0$  is reference evapotranspiration (mm),  $\Delta$  is the slope of the saturated vapor pressure ( $\text{kPa}/^\circ\text{C}$ ),  $R_n$  is net radiation at the surface ( $\text{MJ}/(\text{m}^2 \cdot \text{d})$ ),  $G$  is soil heat flux density ( $\text{MJ}/(\text{m}^2 \cdot \text{d})$ ),  $\gamma$  is the psychrometric constant ( $\text{kPa}/^\circ\text{C}$ ),  $T$  is the mean air temperature at the height of 2 m ( $^\circ\text{C}$ ),  $u_2$  is wind speed at the height of 2 m (m/s),  $e_s$  is saturation vapor pressure (kPa), and  $e_a$  is actual vapor pressure (kPa). Each term in Eq. (1) was obtained using methods described by Allen et al. (1998).

### 3.2. M-K test

The M-K test, which was developed by Mann and Kendall and is superior for detecting linear or non-linear trends (Hisdal et al., 2001), was employed to analyze the long-term trends in  $ET_0$  and air temperature. This method has been widely used for detecting trends in hydro-meteorological variables such as streamflow, air temperature,  $ET_0$ , and precipitation in different regions around the world (Zuo et al., 2012; Gong et al., 2011).

The related equations for calculating the M-K test statistic  $S$  and the standardized test statistic  $Z_{MK}$  are as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(X_j - X_i) \quad (2)$$

$$\text{sgn}(X_j - X_i) = \begin{cases} 1 & X_j - X_i > 0 \\ 0 & X_j - X_i = 0 \\ -1 & X_j - X_i < 0 \end{cases} \quad (3)$$

$$\text{Var}(S) = \frac{1}{18} \left[ n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5) \right] \quad (4)$$

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & S < 0 \end{cases} \quad (5)$$

where  $X_i$  and  $X_j$  are the sequential data values of the time series in the years  $i$  and  $j$ ,  $n$  is the length of the time series,  $t_p$  is the number of ties for the  $p$ th value, and  $q$  is the number of tried values. Positive values of  $Z_{MK}$  indicate increasing trends, while negative values of  $Z_{MK}$  indicate decreasing trends in the time series. When  $|Z_{MK}| > Z_{1-\alpha/2}$ , the null hypothesis, which assumes that there is no significant trend in the time series, is rejected and a significant trend exists in the time series.  $Z_{1-\alpha/2}$  is the critical value of  $Z$  from the standard normal table, and for the 5% significance level the value of  $Z_{1-\alpha/2}$  is 1.96.

### 3.3. Sensitivity coefficient method

For multivariable models, such as the FAO56 P-M method, different variables have different dimensions and ranges of values, which makes it difficult to compare sensitivity with partial derivatives (Zuo et al., 2012). Therefore, the partial derivative is transformed into a non-dimensional form to interpret the sensitivity of the variables (McCuen, 1974; Beven, 1979):

$$S_{V_i} = \lim_{\Delta V_i \rightarrow 0} \left( \frac{\Delta ET_0 / ET_0}{\Delta V_i / V_i} \right) = \frac{\partial ET_0}{\partial V_i} \frac{V_i}{ET_0} \quad (6)$$

$$G_{V_i} = \frac{\Delta V_i}{V_i} S_{V_i} \quad (7)$$

where  $S_{V_i}$  is the sensitivity coefficient and  $V_i$  is the  $i$ th variable.  $S_{V_i}$  represents the subtle change in  $ET_0$  resulting from the subtle change in  $V_i$ .  $G_{V_i}$  indicates the contribution of the  $i$ th variable to the variation of  $ET_0$ . The sensitivity coefficient has been widely used in studies on evapotranspiration (Estevez et al., 2009). The positive  $S_{V_i}$  of one variable means that the changing trends in  $ET_0$  and the variable are the same, while the negative  $S_{V_i}$  of one variable means that the changing trends in

$ET_0$  and the variable are opposite. It is the same for  $G_{V_i}$ . Sensitivity coefficients are different for different variables at different times. The larger the absolute value of the sensitivity coefficient is, the greater the effect the variable exerts on  $ET_0$ . Also, the larger the absolute value of  $G_{V_i}$  is, the greater the contribution the variable makes to the variation of  $ET_0$ . In this study,  $S_{V_i}$  and  $G_{V_i}$  for daily air temperature, solar radiation, relative humidity, and wind speed were estimated to quantify the contribution of each factor selected to the variation of  $ET_0$ .

## 4. Result analysis and discussion

### 4.1. Temporal trend of $ET_0$

Fig. 2 shows inter-annual variation of seasonal  $ET_0$  in each season. It can be seen that seasonal  $ET_0$  in the middle reaches was similar to that across the whole basin in both values of seasonal  $ET_0$  and the inter-annual trends.

The M-K test was carried out at the 15 stations to investigate the changing trends in annual  $ET_0$  series during the period from 1959 to 2012 in the HRB at the significance level of 5%. The results show that the annual  $ET_0$  series exhibited decreasing trends at most of meteorological stations (Fig. 3(a)). Fig. 3(a) also shows that seven stations in the basin showed a significant decreasing trend. In the legend of Fig. 3, Decrease Sig, Decrease Insig, Increase Sig, and Increase Insig mean decrease significant, decrease insignificant, increase significant, and increase insignificant, respectively.

Changing trends in seasonal  $ET_0$  at each station were also detected using the M-K test. Results reveal that the spring  $ET_0$  of all 15 stations exhibited an insignificant decreasing trend. A decreasing trend in the summer  $ET_0$  took place at most of the 15 stations, except at Yeniugou, Mazongshan, and Guaizihu stations. Of the three stations, Guaizihu Station, located in the lower reaches of the HRB, exhibited a significant increasing trend, while Yeniugou Station in the upper reaches and Mazongshan Station in the lower reaches exhibited an

insignificant increasing trend. In autumn, eight stations showed an increasing trend in  $ET_0$ , much more than in other seasons. For the eight stations, the autumn  $ET_0$  at five stations increased significantly. The other seven stations showed a significant decreasing trend, except for Jiuquan Station and Zhangye Station in the middle reaches. Four stations showed an increasing trend in the winter  $ET_0$ , two of which are located in the upper reaches, while Shandan Station and Guaizihu Station are in the middle and lower reaches, respectively.

Generally, at the temporal scale, most of the stations showed a decreasing trend over the four seasons, especially in spring. An increasing trend in annual and seasonal  $ET_0$  mostly took place at stations in the upper and lower reaches.

### 4.2. Temporal trend of air temperature

In order to investigate the evaporation paradox in the HRB, it is necessary to study the changing trend in air temperature. Fig. 4 shows the results of the M-K test performed on the annual mean air temperature as well as the seasonal mean air temperature. The HRB is dominated by an increasing trend in air temperature at the annual and seasonal scales, with all 15 stations experiencing warmer conditions. The seasonal mean air temperature in autumn and winter increases significantly at most stations, while the increase of the seasonal mean air temperature in spring and summer is insignificant. This means that the increase of air temperature in autumn and winter contributes more to the increase of annual mean air temperature.

### 4.3. Evaporation paradox

As described above, there was a warming trend in the HRB during the period from 1959 to 2012, and annual  $ET_0$  exhibited a decreasing trend in the middle and lower reaches of the HRB. Accordingly, it can be concluded that the evaporation paradox did exist in the HRB, except in the upper reaches and

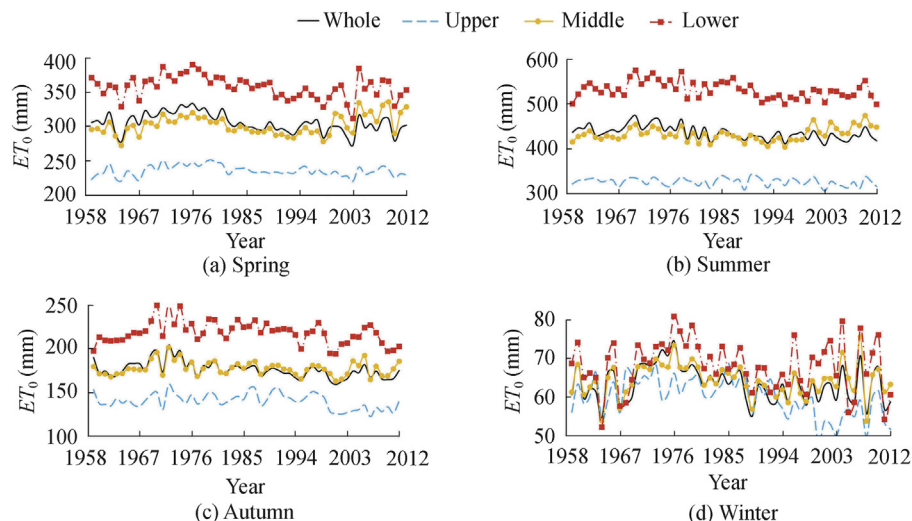


Fig. 2. Temporal variations of seasonal  $ET_0$  of HRB from 1959 to 2012.



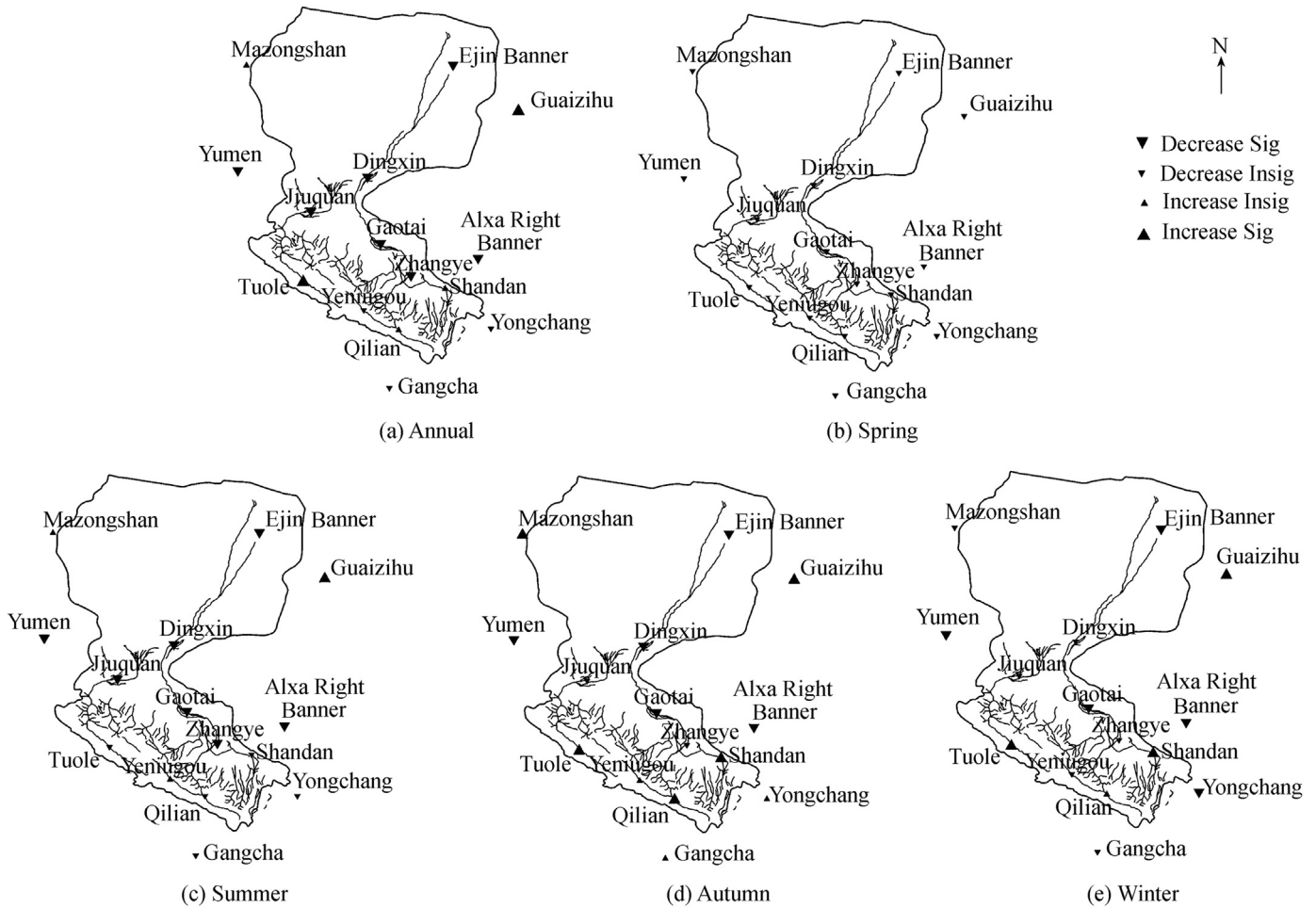


Fig. 3. Spatial distributions of annual and seasonal  $ET_0$  trends in HRB from 1959 to 2012.

at two stations in the lower reaches, where the annual  $ET_0$  showed an increasing trend or an insignificant decreasing trend (Fig. 5). In other words, the evaporation paradox mainly existed in the middle-lower reaches of the HRB.

#### 4.4. Sensitivity of key meteorological factors for $ET_0$

In order to quantify the contribution of key meteorological factors to the spatial and temporal variations of  $ET_0$  and determine the reason why the evaporation paradox exists in the HRB, the sensitivity coefficients of main meteorological variables of  $ET_0$ , i.e., air temperature ( $S_{TA}$ ), solar radiation ( $S_{RS}$ ), relative humidity ( $S_{RH}$ ), and wind speed ( $S_{WS}$ ), in different regions of the HRB were calculated and are plotted in Fig. 6.

From Fig. 6(a), it can be seen that the sensitivities of relative humidity are all negative in different regions of the HRB, which means that  $ET_0$  will decrease when relative humidity increases.  $S_{RH}$  reaches its peak in summer around July and attains its minimum value in December and January. Generally, the curves exhibit a single-peak shape, though they retain fluctuation over short temporal periods.  $S_{RH}$  in the lower reaches is obviously smaller than in other regions. In other words, relative humidity has a greater negative effect on the

variation of  $ET_0$  in the lower reaches than in the upper-middle reaches. Similarly, the sensitivity coefficient curves shown in Fig. 6(b) for the air temperature present a single-peak shape and reach their peak in May and June.  $S_{TA}$  in the lower reaches is higher than in the upper-middle reaches throughout the year. Curves of  $S_{RS}$  (Fig. 6(c)) are similar to those of  $S_{RH}$  and  $S_{TA}$ , reaching their maximum and minimum values in summer and winter, respectively. In the middle-lower reaches, the effect of solar radiation on  $ET_0$  in early summer (May and June) is the greatest, while in the upper reaches the peak comes around a little later in August. Fig. 6(d) shows that, in the middle-lower reaches,  $ET_0$  is more sensitive to wind speed in summer, while  $S_{WS}$  in the upper reaches, which is much smaller than that in the middle-lower reaches, remains almost unchanged throughout the year, and does not show a significant peak.

A comparison of the four subgraphs of Fig. 6 shows that for the four meteorological factors considered in this study, relative humidity was the most sensitive factor for  $ET_0$  at the daily scale with absolute values of sensitivity coefficients reaching 6.0 in summer, several times higher than that of other meteorological factors. Wind speed was the second greatest sensitive factor to  $ET_0$ , especially in the middle-lower reaches.

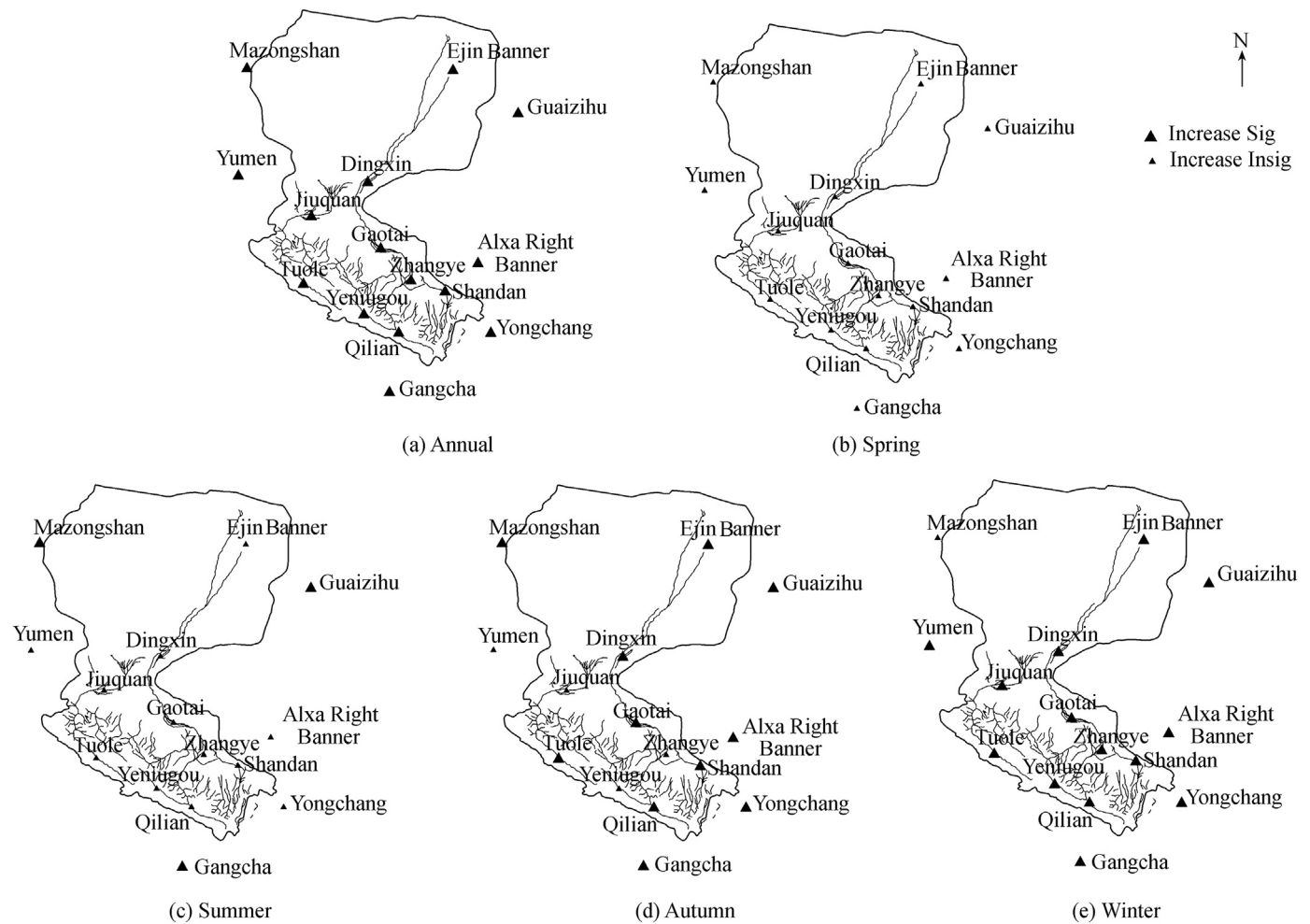


Fig. 4. Spatial distributions of mean annual and seasonal air temperature trends in HRB from 1959 to 2012.

Air temperature and solar radiation were the two least sensitive meteorological factors to  $ET_0$ .

The sensitivity coefficient ( $S_{V_i}$ ) indicates the sensitivity of  $ET_0$  to the meteorological factor ( $V_i$ ), under the condition that

changes in all meteorological factors are the same. However, at the 15 selected stations in the HRB, the changing percentage varies greatly for each meteorological factor. Thus,  $G_{V_i}$  was employed in this study to indicate the relative change in  $ET_0$  resulting from each meteorological factor. Table 1 lists the annual  $G_{V_i}$  value for each meteorological factor estimated by Eq. (7). The total estimated contribution was obtained by summing up the  $G_{V_i}$  of each factor. From the table we can see that, in the upper reaches,  $G_{V_i}$  values of air temperature and solar radiation are much larger than those of other two factors, which means that air temperature and solar radiation contribute the most to the variation of  $ET_0$ , while relative humidity and wind speed hardly make contributions to the variation of  $ET_0$ , due to the quite low relative change of humidity and wind speed in the upper reaches. In the middle reaches, the large decrease in solar radiation and wind speed lead to the decrease in  $ET_0$  at all stations except Shandan Station, which is consistent with results of the changing trend of  $ET_0$  (Fig. 3(a)). Though relative humidity is the most sensitive factor for  $ET_0$ , its relative change is little during the study period, and contributed least to the variation of  $ET_0$ . In the lower reaches, solar radiation and wind speed are the two determining factors for the variation of  $ET_0$  because of their

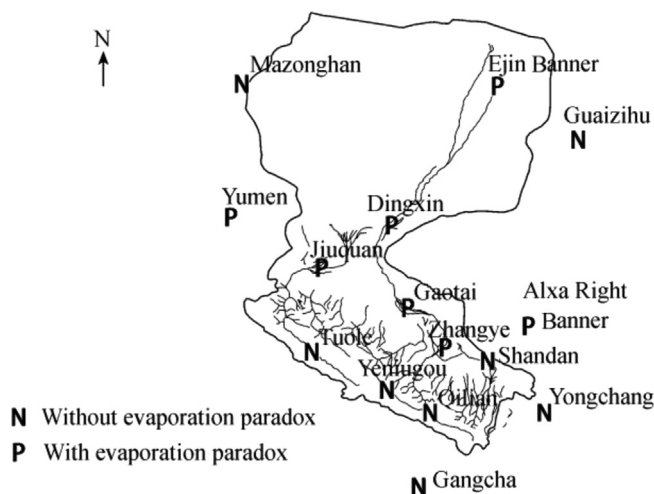


Fig. 5. Evaporation paradox in HRB from 1959 to 2012.

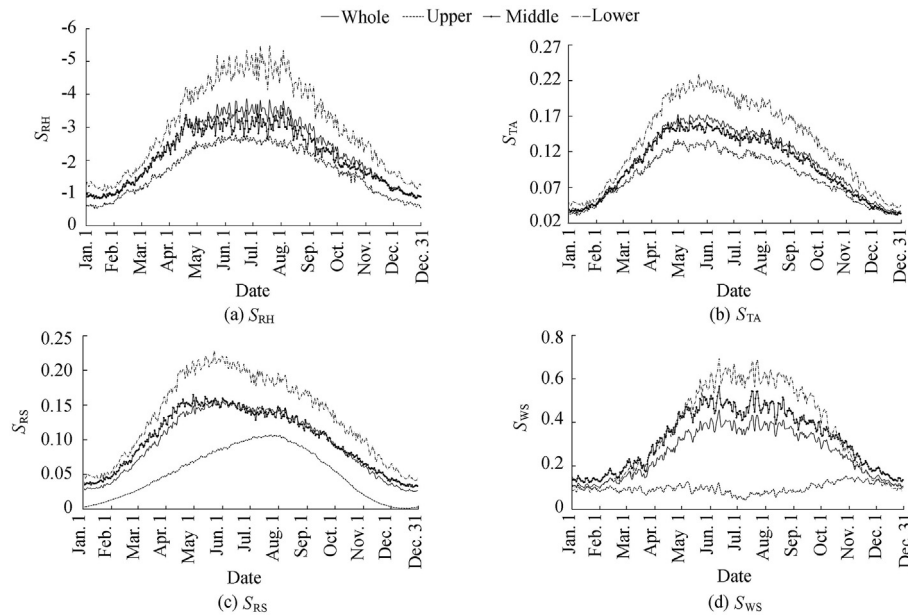


Fig. 6. Sensitivity coefficients in different regions of HRB.

Table 1  
Contribution of meteorological factors to variation of  $ET_0$ .

Station	Region	Air temperature (%)	Solar radiation (%)	Relative humidity (%)	Wind speed (%)	Total contribution (%)
Tuole	Upper reaches	3.00	7.73	0.07	1.65	12.45
Yeniugou		1.58	17.54	0.79	-0.46	19.54
Qilian		5.81	-1.78	0.21	-0.48	3.76
Yongchang		1.30	5.08	1.50	-3.90	3.98
Gangcha		19.49	-6.02	-0.28	-0.44	12.75
Alxa Right Banner	Middle reaches	1.92	-12.06	0.25	-19.21	-29.10
Dingxin		1.34	5.78	-0.54	-7.72	-1.14
Jiuquan		1.13	-0.79	-0.17	-7.05	-6.88
Gaotai		0.64	-12.83	0.38	-17.10	-28.91
Zhangye		1.03	2.50	0.05	-8.92	-5.34
Shandan	Lower reaches	2.40	19.87	-0.55	-2.42	19.30
Ejin Banner		2.43	17.26	-0.55	-21.72	-2.58
Mazhongshan		3.71	7.76	0.04	-0.47	11.04
Guaizihu		3.05	23.17	-0.15	6.10	32.17
Yumen		1.31	-11.72	-0.53	-14.17	-25.11

large impact on  $ET_0$  and significant variations during the study period.

## 5. Conclusions

In this study, temporal variation of  $ET_0$  was estimated using the FAO56 P-M method and key meteorological factors were analyzed at 15 meteorological stations in the HRB during the period from 1959 to 2012. Conclusions can be summed up as follows:

(1) Both annual and seasonal  $ET_0$  for most of the HRB displayed a decreasing trend throughout years, especially in spring. As for air temperature, all 15 stations showed increasing trends, which means that there was a warming trend in the HRB during the period from 1959 to 2012.

(2) From the fact that mean annual  $ET_0$  and air temperature exhibited contrasting trends, it can be concluded that the evaporation paradox did exist in the HRB, mainly in the middle-lower reaches.

(3) The results of sensitivity analysis show that relative humidity was the most sensitive factor for  $ET_0$  at the daily scale in the HRB, followed by wind speed, air temperature, and solar radiation. In the upper reaches, air temperature and solar radiation contributed most to the temporal variation of  $ET_0$ , and in the middle-lower reaches, solar radiation and wind speed were the determining factors for the temporal variation of  $ET_0$ .

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