Variations and Sensitivity Analysis of Reference Evapotranspiration During 2010-2019 in the Zhangye Farmland Oasis, Northwest China

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Research Article

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ABSTRACT

Reference evapotranspiration (ET₀) is an important parameter for agricultural water management in the arid Zhangye farmland oasis. However, the ET₀ variations in this oasis over the last decade and meteorological forcings of these variations are unknown. This study investigated the ET₀ variations during 2010-2019 in this oasis using the FAO-56 Penman-Monteith (PM) and Hargreaves equations. Results showed that the ET₀ features daily and monthly variations with peak values in mid-July and an annual cycle. Although the estimated ET₀ series based on the two equations have high correlations in the time domain, the Hargreaves equation always underestimates the ET₀ compared to the PM equation. The yearly ET₀ showed statistically significant increasing trends (90% significance level) during 2010-2019, while statistically significant increasing trends in monthly ET₀ are found only in March and November. Increasing trends reflected in monthly and yearly ET₀ are mainly attributed to the increasing maximum temperature and sunshine duration and decreasing relative humidity. Sensitivity analysis demonstrated that the meteorological factor to which the ET₀ is most sensitive varies with time scale and equation. Moreover, regression equations used to correct the underestimation associated with the Hargreaves equation for estimating ET₀ in the Zhangye farmland oasis also were constructed.

Introduction

Reference evapotranspiration (ET₀) is an important component of the regional hydrological cycle and is closely related to the biomass and productivity of terrestrial ecosystems. ET₀ is also one of the most important hydrological parameters for agricultural water resources management and estimating actual evapotranspiration. Under the background of rapid global warming, studying ET₀ variability at different spatiotemporal scales can help to maintain regional agricultural production and protect the regional eco-environment. In addition, studies indicated that ET₀ variations feature high spatial heterogeneity, especially in China’s complex geographical and climatic conditions. For example, during the last decade, significant increasing trends in annual ET₀ have occurred in the hilly regions of Southern China, the upper Yangtze River basin, the Pearl River Delta, the non-monsoon region of China, the Huang-Huai-Hai River Basin and the Indo-China Peninsula. In other regions, such as in Heilongjiang Province and the central arid zone of Ningxia Province, annual ET₀ variations have experienced significant decreasing trends. In the Tibetan Plateau and the Loess Plateau, ET₀ variations have been found to have more complex trends than other regions of China, namely both increasing and decreasing trends in the ET₀ were observed in these regions. The Zhangye farmland oasis is located in the Hexi Corridor (102°07'E-103°46'E, 36°31'N-37°55'N), which is a typical arid region in Northwest China. In addition, the Zhangye farmland oasis is the largest corn seed production base in China and uses a large amount of water of the Heihe River during the growing season of corn, giving rise to a conflict between the water requirements of natural ecosystems and agricultural irrigation. Therefore, an understanding of the ET₀ variations during the last decade in this area is important for local agricultural production and oasis eco-environment protection. However, it is still unclear how ET₀ has varied in the Zhangye farmland oasis during the last decade (i.e., 2010-2019) and what are the main meteorological factors driving these variations. Accordingly, the first aim of this study is to investigate the ET₀ variations in the Zhangye farmland oasis during the last decade.

Direct measurements of ET₀ are time-consuming, cumbersome, and expensive. Thus, ET₀ is usually estimated using empirical or hybrid (energy and mass transfer) methods. Commonly-used mathematical equations for estimating ET₀ include the Thornthwaite equation, the Turc equation, the Jensen-Haise equation, the Priestley-Taylor equation, the Hargreaves equation, and the FAO-56 Penman-Monteith equation (PM equation, hereinafter), as well as several variations of the PM equation. These equations have been widely compared with each other and applied in different climatic regions of the world. Previous studies have shown that the PM equation is closest to actual evapotranspiration and is better than other ET₀ estimation equations in many areas with different climatic conditions if all required meteorological factors can be fully satisfied. Usually, the PM equation is accepted as the standard method for estimating the ET₀ and hence it has been adopted as a reference in many studies evaluating the performances of other ET₀ estimation equations. However, the PM equation
requires the full availability of meteorological data including temperature, wind speed, relative humidity and sunshine duration. Globally, there are not many meteorological stations observing all these meteorological parameters. Consequently, the applicability of the PM equation is limited over areas with limited or unavailable meteorological data. The Hargreaves equation is one of the simplest equations used to estimate ET$_0$, previous studies showed that the Hargreaves equation was on par with the PM equation in terms of accuracy for estimating ET$_0$ in the arid and semi-arid climatic conditions$^{24,30}$. In addition, the Thornthwaite equation usually provides very poor ET$_0$ estimates compared to other equations$^{26}$. The Turc equation is one of the most accurate empirical equations but it usually is used to estimate ET$_0$ under humid conditions$^{31}$. The Priestley-Taylor equation is a simplified version of the Penman equation that can be used when for wet surface areas$^{21,29}$.

Based on these considerations, the Hargreaves equation is a more applicable ET$_0$ estimation equation in the arid Zhangye farmland oasis. Accordingly, the second aim of this study is to compare the ET$_0$ variations estimated by the Hargreaves equation to those estimated by the PM equation.

ET$_0$ is jointly affected by several meteorological factors, such as air temperature, wind speed, air humidity, solar radiation and sunshine duration. Different meteorological factors have different effects on ET$_0$ variations$^{32-34}$. Previous studies also showed that the sensitivities of ET$_0$ variations to meteorological factors varied in space and time$^{34-39}$. In order to understand the mechanisms of the regional ET$_0$ variations caused by variability in meteorological factors, researchers have studied the sensitivities of ET$_0$ to main meteorological factors using a variety of sensitivity analysis methods in different regions$^{16,36,38,40-43}$. However, at present, there is still a lack of systematic research on which meteorological factors have the greatest impact on ET$_0$ in the Zhangye farmland during the last decade at different time scales. Therefore, the third aim of this study is to investigate the sensitivities of the ET$_0$ variations estimated by the PM equation and the Hargreaves equation to main meteorological factors (e.g., maximum temperature, $T_{\text{max}}$; minimum temperature, $T_{\text{min}}$; mean temperature, $T_{\text{mean}}$; mean relative humidity, RHU; mean wind speed, WSP; mean sunshine duration, SSD) in the Zhangye farmland oasis during the last decade on daily and monthly time scales.

### Results

#### Variations in ET$_0$

The daily, monthly and yearly ET$_0$ series, which were estimated by the PM and Hargreaves equations based on six meteorological data (see Methods), are presented in Figs. 1-3. The multi-years mean of daily ET$_0$ estimated by the PM equation is 4.05 mm/day over the period of Jan/1/2010-Dec/31/2019. The corresponding value estimated by the Hargreaves equation is 3.06 mm/day. For the monthly ET$_0$, the multi-years mean values estimated by the PM and Hargreaves equations are 122.97 mm/month and 93.11 mm/month, respectively. In addition, for the yearly ET$_0$, the values estimated by the PM and Hargreaves equations are 1475.72 mm/year and 1117.33 mm/year, respectively. Fig. 1 demonstrates that the ET$_0$ values estimated by both of the equations feature apparently daily and monthly variations and an annual cycle. The correlation coefficient between the two daily ET$_0$ series estimated by the two equations is 0.95 ($p < 0.01$) and correlation coefficients between the monthly ET$_0$ series estimated by the two equations from January to December are 0.85, 0.70, 0.94, 0.91, 0.69, 0.71, 0.89, 0.92, 0.92, 0.71, 0.56 and 0.89 ($p < 0.01$), respectively, indicating high correlations in the time domain between the two daily and monthly ET$_0$ series respectively estimated by the two equations in the Zhangye farmland oasis. In addition, the ET$_0$ increases from January to July, with peak values in mid-July, and then decreases from July to December (see Fig. 2a). Note that the estimated ET$_0$ values using the PM equation are always greater than those estimated by the Hargreaves equation on daily, monthly and yearly time scales (see Figs. 1-3). Large differences between the two estimated ET$_0$ series are found in March, April and May. Compared with the PM equation, the main reason for the Hargreaves equation underestimating ET$_0$ may be that the PM equation considers the effects of WSP, RHU and SSD on the evapotranspiration. For example, the water vapor carried by winds is included in the total evapotranspiration estimated by the PM equation, and the role of sunshine in increasing plant transpiration is also considered by the PM equation. In addition, the greater the RHU of the atmosphere, the weaker the plant transpiration; on the contrary, the lower the RHU of the atmosphere, the faster the plant transpiration rate. However, the Hargreaves equation does not take into account the effects of these meteorological factors on evapotranspiration and hence underestimates the actual evapotranspiration compared to the PM equation on different time scales.
This study calculated the 10-years (i.e., 2010-2019) linear trend in monthly ET₀ estimated by the two equations using the linear regression method (see Fig. 3). Statistically significant (90% confidence level, hereinafter) increasing trends in monthly ET₀ were found in March for both of the two estimated ET₀ series (e.g., the trend is 4.12 mm/year for the PM equation and trend is 1.80 mm/year for the Hargreaves equation) and in November only for the PM equation (e.g., the trend is 1.51 mm/year). There is no statistically significant trend in the estimated monthly ET₀ in other months for both of the equations during 2010-2019. Furthermore, there are statistically significant increasing trends in the yearly ET₀ estimated by the PM equation (i.e., 17.28 mm/year) and the Hargreaves equations (i.e., 3.09 mm/year) during 2010-2019 (Fig. 2b). The reasons for these trends reflected in monthly and yearly ET₀ series during 2010-2019 are analyzed in the discussion section.
Figure 3. Variations and trends in monthly $ET_0$ estimated by the PM equation and the Hargreaves equation. Red and blue texts show the trends and significances of monthly $ET_0$ estimated by the PM equation and the Hargreaves equation, respectively.

Sensitivity analysis of $ET_0$

The daily and monthly sensitivity coefficients (SCs) during 2010-2019 were calculated using the sensitivity analysis method (see Methods). Net radiation ($R_n$) is a necessary parameter in the PM equation. In this study, however, it was theoretical estimated based on the observed $T_{max}$, $T_{min}$ and SSD (see Methods) rather than actual observations like $T_{max}$, $T_{min}$ $T_{mean}$, RHU, WSP and SSD. Therefore, in this study, the sensitivity of $ET_0$ to $R_n$ was not analyzed. All of the six observed meteorological parameters (i.e., $T_{max}$, $T_{min}$ $T_{mean}$, RHU, WSP and SSD) were considered in the PM equation, while only the temperature parameters (i.e., $T_{max}$, $T_{min}$ $T_{mean}$) were considered in the Hargreaves equation. The variations of the daily and monthly SCs are presented in Fig. 4 and Fig. 5 and the corresponding statistics of the SCs are summarized in Table S1 and Table S2. Here, for simplicity, the SCs of $ET_0$ to the six meteorological parameters in the PM equation are abbreviated as SC-PM-$T_{max}$, SC-PM-$T_{min}$, SC-PM-$T_{mean}$, SC-PM-RHU, SC-PM-WSP and SC-PM-SSD, respectively. The SCs of $ET_0$ to the $T_{max}$, $T_{min}$ and $T_{mean}$ in the Hargreaves equation are abbreviated as SC-H-$T_{max}$, SC-H-$T_{min}$ and SC-H-$T_{mean}$, respectively.
Figure 4. Daily variations of the SCs of ET\textsubscript{0} to main meteorological factors in Zhangye farmland oasis during 2010-2019.

Fig. 4 demonstrates that the daily SCs feature annual periodic variations for all meteorological parameters considered. The ET\textsubscript{0} is always positively sensitive to SSD (e.g., the range of daily SC-PM-SSD is 0.00~0.52) (see Fig. 4f) and negatively sensitive to RHU (e.g., the range of daily SC-PM-RHU is -4.33~0.03) (see Fig. 4d) in the PM equation. For other meteorological parameters, the SCs are either positive or negative, which varied with the month (see Figs. 5(a)(b)(c) and (e)). For example, roughly, the ET\textsubscript{0} is positively sensitive to other four meteorological parameters (i.e., T\textsubscript{\text{max}}, T\textsubscript{\text{min}}, T\textsubscript{\text{mean}}, and WSP) in warm months and negatively sensitive to these four meteorological parameters in cold months in the PM equation, the ranges of daily SCs associated with the above four meteorological parameters are -0.39~1.14, -0.37~0.39, -0.83~0.49 and -0.27~0.48 in that order. The absolute values of the daily SC-PM-RHU (i.e., mean = 0.51) are apparently greater than those of other five meteorological parameters, suggesting the daily ET\textsubscript{0} is most sensitive to the RHU in the PM equation, followed by the T\textsubscript{\text{max}} (i.e., mean of the absolute values of the daily SC-PM-RHU is 0.43). The absolute values of the daily SC-PM-T\textsubscript{\text{min}} (i.e., mean = 0.10) and SC-PM-T\textsubscript{\text{mean}} (i.e., mean = 0.08) are apparently lower than those of SC-PM-RHU, SC-PM-T\textsubscript{\text{max}}, SC-PM-WSP and SC-PM-SSD, suggesting the daily ET\textsubscript{0} is slightly sensitive to the T\textsubscript{\text{min}} and T\textsubscript{\text{mean}} in the PM equation. Fig. 4g, h and i suggest that the ET\textsubscript{0} is positively sensitive to the T\textsubscript{\text{max}}, T\textsubscript{\text{min}} and T\textsubscript{\text{mean}} in warm months and negatively sensitive to these three meteorological factors in cold months in the Hargreaves equation. The ranges of the daily SC-H-T\textsubscript{\text{max}}, SC-H-T\textsubscript{\text{min}} and SC-H-T\textsubscript{\text{mean}} are -1.66~2.46, -3.57~1.62 and -4.47~0.64, respectively. From the multi-years means of absolute values of the daily SCs during 2010-2019, the ET\textsubscript{0} is most sensitive to T\textsubscript{\text{mean}} (i.e., mean = 4.74) in the Hargreaves equation, followed by T\textsubscript{\text{min}} (i.e., mean = 3.57) and T\textsubscript{\text{max}} (i.e., mean = 2.64).
Figure 5. Monthly variations of the SCs of ET0 to main meteorological factors in the Zhangye farmland oasis during 2010-2019.

Fig. 5 presents the variations of the monthly SCs. The monthly SC-PM-T_{\text{max}} increases from January to May, reaches a peak in May, and then decreases from May to December (Fig. 5a). The monthly SC-PM-SSD increases from January to July, reaches a peak in July, and then decreases from July to December (Fig. 5f). The monthly SC-PM-WSP has a minimum value in July and two maximum values in May and November, respectively (Fig. 5e). In addition, the monthly SC-PM-T_{\text{min}} indicates that the monthly ET0 is positively sensitive to T_{\text{min}} in May, June, July, August, September and October while negatively sensitive to T_{\text{min}} in January, February, March, November and December in the PM equation (Fig. 5b). The monthly SC-PM-T_{\text{mean}} is negative in all months except September; the minimum is found in January. The absolute values of the monthly SC-PM-T_{\text{mean}} are very small compared to other meteorological factors in all months (Fig. 5c). For the RHU, the monthly SC-PM-RHU is negative in all months, it increases from January to May, reaches a maximum in May, and then decreases from May to December (Fig. 5d). Moreover, the absolute values of the monthly SCs indicate that the monthly ET0 is more sensitive to RHU (i.e., mean = 0.51) than T_{\text{max}} (i.e., mean = 0.40), T_{\text{min}} (i.e., mean = 0.10), T_{\text{mean}} (i.e., mean = 0.05), WSP (i.e., mean = 0.22) and SSD (i.e., mean = 0.24) in all months in the PM equation. Furthermore, variations of the absolute values of the monthly SC-PM-WSP (i.e., var < 0.001) and SC-PM-SSD (i.e., var < 0.001) are relatively stable in all months compared to the variations of the absolute values of the monthly SC-PM-T_{\text{max}} (i.e., var = 0.05) and SC-PM-RHU (i.e., var = 0.04). Fig. 5g indicates that in the Hargreaves equation the monthly ET0 is positively sensitive to T_{\text{max}} in all months except in January. The monthly SC-H-T_{\text{mean}} increases from January to July, reaches a peak in July, and then decreases from July to December. In addition, the monthly ET0 is positively sensitive to T_{\text{min}} in January, February, March, November and December and negatively sensitive to T_{\text{min}} in May, June, July, August, September and October, with a dip in July in the Hargreaves equation (Fig. 5h). The monthly ET0 is positively sensitive to T_{\text{mean}} in March to October and negatively sensitive to T_{\text{mean}} in January, February, November and December in the Hargreaves equation (Fig. 5i). The monthly SC-H-T_{\text{min}} and SC-H-T_{\text{mean}} show almost opposite phases by comparing Fig. 5h and Fig. 5i. The means of the absolute values of the monthly SCs indicate that the monthly ET0 is most sensitive to T_{\text{max}} (i.e., mean = 0.56), followed by T_{\text{min}} (i.e., mean = 0.50) and T_{\text{mean}} (i.e., mean = 0.41) in the Hargreaves equation.
Discussion

Since the PM equation takes into account more meteorological parameters affecting evapotranspiration (e.g., wind, air humidity and sunshine) and physical processes of crop evapotranspiration compared to other ET$_0$ estimation equations, previous studies confirmed that ET$_0$ estimated by the PM equation is closest to actual evapotranspiration. In this study, ET$_0$ estimated by the Hargreaves equation is lower than that estimated by the PM equation at different time scales. This underestimation associated with the Hargreaves equation is more apparent in March, April and May than those in other months (Fig. 2a and Fig. 3). This is, possibly, because the ET$_0$ is positively sensitive to the WSP and negatively to the RHU in the PM equation, and the WSP values in April and May are apparently larger than those in other months and the RHU values in March, April and May are apparently smaller than those in other months during 2010-2019 in the Zhangye farmland oasis (see Fig. S1). In addition, the Zhangye farmland oasis is a typical arid area in which the scarcity of meteorological data is still apparent compared to the Eastern China, thus, the Hargreaves equation has a great application potential in this area due to its inherent advantages of estimating ET$_0$ in arid areas and the simplicity of data requirements. However, results demonstrate that there are apparent deviations in the time domain between the two daily and monthly ET$_0$ series respectively estimated by the two equations in the Zhangye farmland oasis though there are high correlations between the two ET$_0$ series. Therefore, it is necessary to correct the coefficients of the Hargreaves equation and further to improve its accuracy for estimating ET$_0$ in the Zhangye farmland oasis. In order to achieve this goal, this study established linear regression equations based on the estimated daily and monthly ET$_0$ series. In these regression equations, the ET$_0$ estimated by the PM equation is dependent variable and the ET$_0$ estimated by the Hargreaves equation is independent variable. The established regression equation on daily ET$_0$ is presented in Eq. (1). The established regression equations on monthly ET$_0$ are presented in Table 1. When using the Hargreaves equation to estimate ET$_0$ in other areas of the Zhangye farmland oasis without fully observed meteorological data, these regression equations can be used to correct the ET$_0$ estimated by the Hargreaves equation so that the ET$_0$ estimated by the Hargreaves equation is closer to those estimated by the PM equation.

$$ET_{0-PM} = 0.55 + 1.14 \times ET_{0-H} \quad (R^2 = 0.89) \quad (1)$$

| Month | Linear regression equation | $R^2$ |
|-------|----------------------------|-------|
| 1     | $ET_{0-PM} = 1.70 \times ET_{0-H} + 8.46$ | 0.72  |
| 2     | $ET_{0-PM} = 1.53 \times ET_{0-H} + 8.37$ | 0.49  |
| 3     | $ET_{0-PM} = 2.00 \times ET_{0-H} - 34.33$ | 0.89  |
| 4     | $ET_{0-PM} = 2.15 \times ET_{0-H} - 84.23$ | 0.83  |
| 5     | $ET_{0-PM} = 1.97 \times ET_{0-H} - 102.80$ | 0.46  |
| 6     | $ET_{0-PM} = 1.18 \times ET_{0-H} + 3.72$ | 0.51  |
| 7     | $ET_{0-PM} = 1.05 \times ET_{0-H} + 19.74$ | 0.79  |
| 8     | $ET_{0-PM} = 1.42 \times ET_{0-H} - 41.15$ | 0.85  |
| 9     | $ET_{0-PM} = 1.73 \times ET_{0-H} - 53.26$ | 0.84  |
| 10    | $ET_{0-PM} = 2.09 \times ET_{0-H} - 45.13$ | 0.50  |
| 11    | $ET_{0-PM} = 0.51 \times ET_{0-H} + 37.69$ | 0.38  |
| 12    | $ET_{0-PM} = 1.74 \times ET_{0-H} + 4.41$ | 0.80  |

Table 1. Regression equations of monthly ET$_0$ estimated by the Hargreaves equation and the PM equation.

Statistically significant increasing trends in monthly ET$_0$ are found only in March for both of the two ET$_0$ series (Fig. 3c). The reasons behind this result may be that the monthly $T_{max}$ and SSD show statistically significant increasing trends only in March during 2010-2019, and the monthly ET$_0$ is positively sensitive to $T_{max}$ and SSD in March in the PM equation (Fig. 5a,f). The monthly RHU in March during 2010-2019 showed a statistically significant decreasing trend (Fig. S5) and the monthly ET$_0$ is negatively sensitive to the RHU in the PM equation. In addition, although the monthly $T_{mean}$ showed a statistically significant increasing trend in March during 2010-2019 and the monthly ET$_0$ is negatively sensitive to the $T_{mean}$ in the PM equation, the monthly SC-PM-$T_{mean}$ is apparently smaller than the monthly SC-PM-$T_{max}$ and SC-PM-RHU, and thus result in an increasing trend in the monthly ET$_0$ in March during 2010-2019 under the dominating influences of the $T_{max}$ and RHU. Moreover, the monthly ET$_0$ in March is positively sensitive to the $T_{max}$, $T_{min}$ and $T_{mean}$ in the Hargreaves equation (Fig. S5g,h,i). The monthly $T_{max}$ and $T_{mean}$ showed statistically significant increasing trends in March and the monthly $T_{min}$ showed no statistically significant trend in March during 2010-2019. Therefore, under the joint influences of $T_{max}$ and $T_{mean}$, the monthly ET$_0$ in March estimated by the Hargreaves equation showed an increasing trend during 2010-2019. Furthermore, the monthly ET$_0$ did not show statistically significant trends in other months, which may be due to the fact that there is no statistically significant trend in the six meteorological parameters in most of those months during 2010-2019 (Figs. S2-S7), especially for the two most sensitive parameters (i.e., $T_{max}$ and RHU) (Fig. S2 and Fig. S5). Finally, the two yearly ET$_0$ series also showed statistically significant increasing trends. This may result from the joint influences of statistically significant
increasing yearly $T_{\text{max}}$, WSP and SSD and decreasing yearly RHU during 2010-2019 in the Zhangye farmland oasis (Fig. S8).

The common meteorological parameters contained in the PM equation and the Hargreaves equation are $T_{\text{max}}$, $T_{\text{min}}$ and $T_{\text{mean}}$. However, although the SC-PM-$T_{\text{max}}$ is very similar to the SC-H-$T_{\text{max}}$ in term of monthly variation, the sensitivities of $ET_0$ to $T_{\text{mean}}$ and $T_{\text{min}}$ in the PM equation are apparently different from those in the Hargreaves equation. For example, from the Fig. 5, the monthly SC-PM-$T_{\text{mean}}$ is positive in all months while the monthly SC-H-$T_{\text{mean}}$ is negative in most months except January, February, November and December. The monthly SC-PM-$T_{\text{min}}$ is positive in January, February, March, November and December and is positive from April to October. While the variation of the monthly SC-H-$T_{\text{min}}$ is exactly opposite to that of the monthly SC-PM-$T_{\text{min}}$, namely the monthly SC-H-$T_{\text{min}}$ is negative in January, February, March, November and December and is negative from April to October. This different sensitivities of $ET_0$ to the same temperature variable in various equations implies that temperature has different or even opposite effects on estimating $ET_0$ depending on the equation, because each $ET_0$ method is based on a different physical mechanism. Therefore, when explaining the influence of temperature on estimating $ET_0$, we may not rely on the results of a single equation.

In addition, although the sensitivity analysis method (i.e., the SC method) used in this study is a widely-used method to investigate the response of $ET_0$ to meteorological parameters, it has some drawbacks. Specifically, the prerequisite of the SC method is that there is only one variable can be changed each time, while the other variables remain unchanged. However, in fact, there is usually a covariant relationship between meteorological variables. For example, a change of the mean temperature is often accompanied by simultaneous changes of the maximum temperature and the minimum temperature. In addition, there is a strong connection between relative humidity and air temperature. Increasing (decreasing) air temperature is often accompanied by simultaneous changes of the maximum temperature and the minimum temperature. In fact, there is usually a covariant relationship between meteorological variables. For example, a change of the mean temperature is often accompanied by simultaneous changes of the maximum temperature and the minimum temperature. Increasing (decreasing) air temperature will lead to a decrease (increase) in relative humidity. Therefore, theoretically, the use of a global sensitivity analysis method to study the response of the $ET_0$ to the global changes of multiple meteorological factors in the Zhangye farmland oasis is more reasonable than the use of the SC method. However, this is an ongoing work which will be presented in future.

In summary, agricultural irrigation in the Zhangye farmland oasis requires a large amount of water. $ET_0$ is a key variable in agricultural water management, farmland ecosystems and the hydrological cycle. Thus, it is of great significance to study $ET_0$ variations and meteorological forcings behind these variations in the Zhangye farmland oasis. In this study, the variations of daily, monthly and yearly $ET_0$ estimated by the PM and Hargreaves equations during 2010-2019 in the Zhangye farmland oasis were analyzed and compared with each other. In addition, the sensitivities of $ET_0$ to six major meteorological parameters effecting crop evapotranspiration were also investigated on daily and monthly time scales using the SC method. Particularly, regression equations used to correct the underestimation associated with the Hargreaves equation for estimating $ET_0$ in the Zhangye farmland oasis are also constructed. All findings provide a scientific basis for understanding $ET_0$ variations and the sensitivity of the $ET_0$ to main meteorological parameters in the Zhangye farmland oasis during the last decade, and can help improve agricultural water resources management and oasis environmental protection in the Zhangye farmland oasis.

Methods

Meteorological data

Daily data for the six meteorological parameters were downloaded from the China Meteorological Data Network (http://data.cma.cn/data/). These meteorological data were observed by the Zhangye national meteorological reference station (station number: 52652; longitude: 100.17 E; latitude: 39.05 N; altitude: 1461.10 m). Daily $T_{\text{mean}}$ was calculated according to the mean of the temperature observed at 02:00, 08:00, 14:00 and 20:00 (Beijing time) rather than the mean of daily $T_{\text{max}}$ and $T_{\text{min}}$. The daily, monthly and yearly $ET_0$ from January/1/2010 to December/31/2019 were calculated based on these meteorological data.

The FAO-56 Penman-Monteith equation

The FAO-56 Penman-Monteith equation (hereinafter PM equation) is based on the energy balance and water vapor diffusion theory and overcomes several shortcomings associated with previous Penman equations. Because the PM equation is currently the most accurate method for estimating $ET_0$ in both humid and arid climatic conditions, it was recommended by the FAO as the only method to estimate the $ET_0$ when all the required meteorological data are available. In addition, the PM equation also has been considered as a standard method to evaluate other $ET_0$ estimation equations. The PM equation to estimate $ET_0$ (mm/d) is:

$$ET_0 = \frac{0.408 \times \Delta \times (R_n - G) + \gamma \times \frac{900}{T_{\text{mean}}} + 237 \times u_2 \times (e_s - e_a)}{\Delta + \gamma \times (1 + 0.34 \times u_2)}$$

Where: $ET_{0c}$: reference evapotranspiration (unit: mm·d$^{-1}$); $e_s$: saturation vapour pressure (unit: kPa); $e_a$: actual vapour pressure (unit: kPa); $\Delta$: slope vapour pressure curve (unit: kPa·°C$^{-1}$); $\gamma$: psychrometric constant (unit: kPa·°C$^{-1}$); $u_2$: wind speed at 2 m height (unit: m·s$^{-1}$); $T_{\text{mean}}$: mean daily air temperature at 2-m height (unit: °C); $G$: soil heat flux (unit: MJ·m$^{-2}$·day$^{-1}$); $R_n$: net radiation at the crop surface (unit: MJ·m$^{-2}$·day$^{-1}$);
All parameters in the above equation can be theoretically estimated according to the FAO methods provided that the $T_{\text{max}}$, $T_{\text{min}}$, latitude and altitude data are known\textsuperscript{23}. The value of soil heat flux $G$ is very small compared to $R_n$; in the case of time steps greater than or equal to 1 day, the value of $G$ is approximately 0 and may often be ignored$^3,23$. In this study, the daily radiation data of the Zhange meteorological station from January/1/2010 to December/31/2019 did not form a continuous time series and also did not meet the criterion for time series interpolation because of a lot of missing values in the raw observation series. Therefore, this study used the theoretically estimated $R_n$, which was calculated based on the observed $T_{\text{max}}$, $T_{\text{min}}$ and SSD data, the meteorological location and astronomical parameters\textsuperscript{23}. The process of estimating $R_n$ was as follows. First, this study calculated the total solar radiation reaching the ground ($R_n$, also known as solar short-wave radiation) based on the observed SSD and the Angstrom-Prescott equation\textsuperscript{23}. The Angstrom-Prescott equation is expressed as follows:\textsuperscript{23}

$$
R_n = (a_s + b_s \cdot \frac{n}{N}) \cdot R_a
$$

Where: $R_n$: solar or shortwave radiation reaching the earth's surface (unit: MJ·m$^{-2}$·day$^{-1}$); $R_a$: extraterrestrial (solar) radiation (unit: MJ·m$^{-2}$·day$^{-1}$); $a_s$ and $b_s$: regression constant, the values $a_s = 0.25$ and $b_s = 0.50$ are recommended by the FAO when no actual solar radiation data are available; $n$: actual duration of sunshine (unit: h); $N$: maximum possible duration of sunshine or daylight hours (unit: h);

$R_a$ can be calculated based on the meteorological location and astronomical parameters\textsuperscript{23}. On the basis of the estimated $R_n$ and $R_a$, the net radiation $R_n$ can be gained by calculating the difference between the incoming net shortwave and the net outgoing longwave\textsuperscript{23}. $R_n$ is normally positive during the daytime and negative during the nighttime.

**The Hargreaves equation**

The Hargreaves equation was established for estimating evapotranspiration in the western arid regions of the USA\textsuperscript{22}. The input variables required by this equation are very simple. All we need to know are $T_{\text{max}}$, $T_{\text{min}}$, $T_{\text{mean}}$ and $R_n$. $T_{\text{mean}}$ can be replaced by the mean of $T_{\text{max}}$ and $T_{\text{min}}$ in case of missing $T_{\text{mean}}$ data\textsuperscript{29}. All meteorological stations measure $T_{\text{max}}$, $T_{\text{min}}$ and $T_{\text{mean}}$, so they are easy to obtain. $R_n$ can be computed based on the meteorological station location and astronomical parameters\textsuperscript{23}. Because of the easy accessibility of the input variables of the Hargreaves equation compared to other equations for estimating $ET_0$, the Hargreaves equation has been widely used in arid and semi-arid regions, especially in places where observational data are scarce, such as Africa, Northwest China and arid central Asia. The form of the Hargreaves equation is as follows:

$$
ET_0 = 0.0023 \cdot 0.408 \cdot R_n \cdot (T_{\text{max}} - T_{\text{min}})^{0.5} \cdot (T_{\text{mean}} + 17.8)
$$

Where: $T_{\text{max}}$: daily maximum temperature at 2-m height (unit: °C); $T_{\text{min}}$: daily minimum temperature at 2-m height (unit: °C); $T_{\text{mean}}$: mean daily temperature at 2-m height (unit: °C); $R_n$: extraterrestrial (solar) radiation (unit: MJ·m$^{-2}$·day$^{-1}$);

**Sensitivity analysis method**

Sensitivity analysis is used to identify the extent to which the variability in the input values for a given variable (e.g., air temperature, wind speed, air humidity and sunshine duration in this study) will impact the result (e.g., $ET_0$ in this study) in a mathematical model, and further calculate the degree of influence of these input variables on the result\textsuperscript{45,46}. Currently, several sensitivity analysis methods have been proposed, of which the sensitivity coefficient (SC) method is a frequently-used method in earth sciences\textsuperscript{47}, especially in studying the sensitivity of the $ET_0$ to meteorological factors\textsuperscript{16,36,43,48-50}. The SC method was first proposed by McCuen\textsuperscript{45}, and the SC is calculated by using the partial derivative of $ET_0$ to various meteorological factors, namely the ratio between the relative variation of $ET_0$ and the relative variation of a meteorological factor. The SC method varies one parameter (e.g., adding perturbation to this parameter) while keeping other parameters constant, and observes the variations of the model outputs before and after adding this perturbation to the parameter. However, currently, there is no universal rule for determining how much the perturbation will be added to the parameter. Therefore, in the sensitivity analysis of this study, specifically, the perturbation is $\beta$ times the value of a meteorological variable, where $\beta$ is a constant randomly sampled from a uniform distribution (0–20%)$^{46}$. The form of the SC method is as follows:

$$
S_{V_i} = \lim_{\Delta V_i \to 0} \frac{\Delta ET_0}{\Delta V_i} \cdot \frac{ET_0}{V_i} = \frac{\partial ET_0}{\partial V_i} \cdot \frac{V_i}{ET_0} \cdot \beta
$$

Where: $S_{V_i}$: SC of the $i^{\text{th}}$ variable, unitless; $V_i$: $i^{\text{th}}$ variable; $\partial ET_0$: change amount of $ET_0$; $\Delta V_i$: change amount in the $i^{\text{th}}$ variable; $\beta$: perturbation coefficient. A positive SC indicates that $ET_0$ increases with the increase of meteorological parameters, and vice versa. Moreover, the larger the absolute value of SC associated with one meteorological parameter, the higher the sensitivity of $ET_0$ to this meteorological parameter, and vice versa.
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Author contributions statement

M.F. conducted the experiment, analyzed the results and drafted the manuscript.

Competing interests

The author(s) declare no competing interests.
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