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Climatic controls on watershed reference evapotranspiration vary dramatically during the past 50 years in southern China

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Abstract

Reference evapotranspiration (ETo) is an important hydrometeorological term widely used in water resource management, hydrological modeling, and understanding and projecting the hydrological effects of future climate change and land use change. Identifying the individual climatic controls on ETo helps better understand the processes of global climatic change impacts on local water resources and also simplify modeling efforts to predict actual evapotranspiration. We conducted a case study on the Qinhuai River Basin (QRB), a watershed dominated by a humid subtropical climate and mixed land uses in southern China. Long term (1961−2012) daily meteorological data at six weather stations across the watershed were used to estimate ETo by the FAO−56 Penman−Monteith model. The seasonal and annual trends of ETo were examined using the Mann−Kendall nonparametric test. The individual contributions from each meteorological variable were quantified by a detrending method. The results showed that basin-wide annual ETo had a decreasing trend during 1961−1987 due to decreased wind speed (WS), solar radiation (R_s), vapor pressure deficit (VPD), and increased relative humidity (RH). These variables had different magnitudes of contribution to the ETo trend in different seasons examined during 1961−1987. However, during 1988−2012, both seasonal and annual ETo showed an increasing trend, mainly due to increased VPD and decreased RH and, to lesser extent, to decreased absolute humidity (AH) and a rising air temperature. We show that the key climatic controls on ETo have dramatically shifted as a result of global climate change during the past five decades. Now the

atmospheric demand, instead of air temperature alone, is a major control on ETo. Thus, we conclude that accurately predicting current and future ETo and hydrological change under a changing climate must consider changes in VPD (i.e., air humidity and temperature) in the study region. Water resource management in the study basin must consider the increasing trend of ETo to meet the associated increasing water demand for irrigation agriculture and domestic water uses.

1 Introduction

In the past three decades, dramatic climate change and human activities have altered global hydrological cycles including the evapotranspiration (ET) processes (Xu et al., 2015; Zalewski, 2000), resulting in a series of environmental and socio-economic impacts (Roderick et al., 2002). Indeed, ET is a key component of water and energy balances, an important topic in modern ecohydrological, meteorological, agricultural, and ecological studies (Yang et al., 2012; Zhao et al., 2014). Reference ET (ETo) which is defined as the rate of ET over a hypothetical underlying surface with fixed parameters is an essential component in estimating actual ET (Liu et al., 2017), hydrological modeling, and projecting the impact of changing weather conditions on water supply (Allen et al., 1998; Liu et al., 2010). McMahon et al. (2013) provided summary of techniques to estimate reference ET and suggested that the FAO−56 Penman−Monteith model was widely adopted and preferred in humid regions. Quantifying the individual role of climatic factors in controlling ETo is important for understanding the influence of climatic change on hydrologic processes in terrestrial ecosystems (Fan and Thomas, 2012; Chen et al., 2006). These investigations have remarkable theoretical and practical significance for understanding watershed hydrological cycle and effective use of farming water resources (Yang et al., 2014; Xu et al., 2015).

Worldwide, numerous studies have examined the trends of ETo in many different regions but with different findings. Significant decreasing trends of ETo have been found in several river basins such as the Platte River Basin in central Nebraska in the USA during 1893−2007 (Irmak et al., 2012), the Tons River Basin, central India during 1969−2008 (Darshana et al., 2013), and China's Qinghai-Tibetan plateau during 1971−2004 (Zhang et al., 2009) and Yunnan province during 1961−2004 (Fan et al., 2013). These studies showed that decreased ETo occurred in some regions despite the global temperature has increased by 0.13 ℃ per decade in the last 50 years (IPCC, 2007).

The variable climatic controls on ETo have been examined under different climatic regimes. Jhajharia et al. (2012) found the decreased WS and declined net radiation overwhelmed the effect of increased air temperature, causing the decreased ETo in a humid region in northeast India during 1978−2002. In western Iran, the increasing trend of ETo was mainly caused by a significant increase in air temperature during 1966−2005 (Tabari et al., 2011a). No changes in ETo were found from 1964 to 1998 in Bet Dagan on Israel's central coastal plain because the effects of rising aerodynamic term were counterbalanced by the decreasing radiation term (Cohen et al., 2002).

In China, similar climate attribution studies have been conducted in different regions. Chen et al.

(2011) proposed that the decrease in ETo in the Sichuan Basin of southwestern China was mainly due to the decreased sunshine hours. Zhang et al. (2010) found the combined effects of decreased WS and sunshine hours offset the impact of increased air temperature, and then caused the decreased ETo in northeast China. Yang et al. (2014) proposed that increased maximum temperature was the main reason for the rise of ETo in Taohe River basin in northwest China during 1981−2010.

Our review of literatures suggests that (i) few studies have been carried out in the humid region of southern China, (ii) both increasing and decreasing trends of ETo were detected in different regions of China and elsewhere, and (iii) not only air temperature affected changes of ETo but also other meteorological variables including wind speed (WS), solar radiation (R_s), relative humidity (RH), absolute humidity (AH), and vapor pressure deficit (VPD) affected ETo to different extent. Therefore, there is a need to study the long term trend of ETo and comprehensive influence of various climatic factors to ETo in humid regions of southern China.

The Qinhuai River Basin (QRB) used for this case study has a subtropical climate typical of the lower Yangtze River Delta region in China. The region is rapidly developing and has been facing more environmental challenges such as land subsidence, water pollution, flooding, and urban heat islands (UHIs) (Liu et al., 2013; Zhao et al., 2014; Zhou et al., 2014). The QRB includes several cities with a population over 8 million and water demand for drinking, irrigation and industry use has placed great pressure on water resources management in this “water rich” region. Our previous study (Hao et al.,

2015) suggests that rapid urbanization by converting paddy fields and water withdrawal for large-scale irrigation in this basin have dramatically altered the watershed hydrology through changes in ET and surface water. A further understanding of the climatic control on ETo could provide valuable information to understand watershed hydrological processes and projecting the impacts of climatic change and land use change on water resources in this basin.

Based on previous studies on ETo in the humid region, we proposed two hypotheses to guide our research: (i) ETo has significantly increased during the past 50 years in the QRB, (ii) In addition to the increased air temperature, other meteorological variables have influenced ETo variation to a different degree. In this study, we aimed to: (i) calculate the ETo over the QRB for the period of 1961–2012 by the FAO−56 Penman−Monteith model, (ii) determine the trends of ETo and eight key meteorological variables with the Mann-Kendall (MK) nonparametric test, and (iii) identify the dominant climatic factors in changing ETo at seasonal and annual scales by a detrending method.

2 Material and methods

2.1 Study area and databases

The QRB is located in the southwest of Jiangsu province (118°39′−119°19′ E, 31°34′−32°10′ N) (Fig.1) and possesses an area of 2617 km^2 including Nanjing, Lishui, and Jurong cities. The land use is dominated by paddy rice field and dry cropland (60 %). The watershed has a flat topography with

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-241, 2017
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Hydrology and Earth System Sciences
Open Access
Discussions

elevation ranging from 0 to 412 m. The QRB has experienced a dramatic urbanization during the past several decades (Du et al., 2012). By 2013, the built-up land has expanded to nearly 1/4 of the whole basin (Fig. 1). Irrigated paddy field covers nearly 35 % of the basin representing the dominant land use.

Daily meteorological data from six standard weather stations in and around the QRB from 1961 to 2012 were provided by the China Meteorological Data Sharing Service System and Jiangsu Weather Bureau. Necessary variables to estimate ETo included WS (m s^{-1}); RH (%); sunshine duration (n, h); daily mean temperature (T_{mean}, ℃); daily maximum and minimum temperature (T_{max} and T_{min}, ℃). Data from Jiangning station was available before 2007. The QRB is dominated by paddy rice field and the rice growing season is between May and October when flood irrigation is needed (Hao et al., 2015). Accordingly, besides four seasons and the annual scale, we also examined the rice growing season as the sixth study period.

2.2 FAO-56 Penman-Monteith model for estimating ETo

The FAO Penman−Monteith (P−M) model has been widely used to estimate ETo and applicable to humid conditions (Allen et al., 1998; McMahon et al., 2013). This model can be expressed:

$$\mathrm{ET_o}\ \frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T+273}U_2(e_s-e_a)}{\Delta+\gamma(1+0.34U_2)} \tag{1}$$

where Δ is the slope of the saturated vapor pressure curve (kPa $℃^{-1}$), R_n the net radiation (MJ m^{-2} day^{-1}), G the soil heat flux density (MJ m^{-2} day^{-1}) (zero on the daily scale), T the mean daily air

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-241, 2017
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Discussion started: 2 May 2017

Hydrology and Earth System Sciences
Open Access
Discussions

temperature (℃), U_2 the mean daily wind speed at 2 m height (m s^{-1}), e_s the saturated vapor pressure (kPa), e_a the actual vapor pressure (kPa), $e_s - e_a$ the Vapor pressure deficit (kPa), and γ the psychrometric constant (kPa ℃$^{-1}$).

Key radiation part in P−M model was estimated by following equations:

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

$$\mathrm{R_{ns}} = (1-\alpha)\mathrm{R_s} \tag{3}$$

$$\mathrm{R_s} = \left(a + \mathrm{b}\frac{\mathrm{n}}{\mathrm{N}}\right)\mathrm{R_a} \tag{4}$$

$$\mathrm{R_{nl}} = \sigma\left(\frac{\mathrm{T_{max,k}^4}+\mathrm{T_{min,k}^4}}{2}\right)\left(0.34 - 0.14\sqrt{\mathrm{e_a}}\right)\left(1.35\frac{\mathrm{R_s}}{\mathrm{R_{so}}} - 0.35\right) \tag{5}$$

where R_{ns} and R_{nl} are the incoming net shortwave and outgoing net longwave radiation (MJ m^{-2} d^{-1}), α the albedo fixed as 0.23, R_s the solar radiation (MJ m^{-2} d^{-1}), n and N the actual and maximum possible sunshine hours (h) respectively, R_a extraterrestrial radiation (MJ m^{-2} d^{-1}), σ the Stefan-Boltzmann (4.903×10^{-9} MJ m^{-2} d^{-1}), $\mathrm{T_{max,k}}$ and $\mathrm{T_{min,k}}$ the maximum and minimum absolute temperature within 24 hours (K), R_{so} the clear sky solar radiation (MJ m^{-2} d^{-1}), a and b the empirical coefficients of 0.25 and 0.5 (Allen et al., 1998).

The VPD (kPa) is calculated as (Allen et al., 1998):

$$\mathrm{VPD} = e_s - e_a \tag{6}$$

where e_s (kPa) can be calculated from T_{max} and T_{min}:

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-241, 2017
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Discussion started: 2 May 2017

Hydrology and Earth System Sciences
Discussions
Open Access

$$\mathrm{e_s} = \frac{\mathrm{e^0(T_{max}) + e^0(T_{min})}}{2} \tag{7}$$

$$\mathrm{e^0(T_{max})} = 0.6108 \exp\left[\frac{17.27\mathrm{T_{max}}}{\mathrm{T_{max}}+273.3}\right] \tag{8}$$

$$\mathrm{e^0(T_{min})} = 0.6108 \exp\left[\frac{17.27\mathrm{T_{min}}}{\mathrm{T_{min}}+273.3}\right] \tag{9}$$

Finally, we computed e_a (kPa) with the e_s and measured daily mean relative humidity (RH):

$$\mathrm{e_a} = \mathrm{e_s} * RH \tag{10}$$

Absolute humidity (AH, g m^{-3}) was calculated with e_a:

$$\mathrm{AH} = \mathrm{c}\frac{\mathrm{e_a}}{\mathrm{T}} \tag{11}$$

where c is a constant with 217 (Xie et al., 2014).

2.3 Mann-Kendall (MK) test

The nonparametric MK test (Mann 1945; Kendall 1975) was applied to analyze the trends of seasonal and annual ETo in many hydrological studies (Li et al., 2013; Liu et al., 2010; Fan et al., 2016). The statistic S is calculated as

$$S = \sum_{k=1}^{n-1}\sum_{j=k+1}^{n} sgn\left(X_j - X_k\right) \tag{12}$$

where X_j represents the sequential data values, n is the number of the dataset, and

$$sgn\left(X_j - X_k\right) = \begin{cases} 1 \;\; if X_j - X_k > 0 \\ 0 \;\; if X_j - X_k = 0 \\ -1 \; if X_j - X_k < 0 \end{cases} \tag{13}$$

When n is greater than 10, S is approximately normally distributed with E(S) = 0 and variance of statistic S can be calculated by:

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{w=1}^{v} t_p\,(t_w - 1)(2t_w + 5)\right] \tag{14}$$

where v is the number of tied groups and t_w is number of data values in wth group.

The standard test statistic (Z) is:

$$Z = \begin{cases} \frac{s-1}{\sqrt{Var(s)}} if s > 0 \\ 0 \quad if s = 0 \\ \frac{s+1}{\sqrt{Var(s)}} if s < 0 \end{cases} \tag{15}$$

The null hypothesis *H0* is rejected when $|Z| > Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is the standard normal deviates.

2.4 Theil-Sen's estimator

Theil-Sen's estimator method was used to estimate magnitudes of ETo trends (Sen 1968; Hirsh 1982)

$$\beta = Median\left(\frac{X_j - X_k}{j-k}\right), 1 < k < j < n \tag{16}$$

where β is the estimated magnitude of slopes of ETo trends. $\beta > 0$ represents an increasing trend; $\beta < 0$ represents a decreasing trend.

2.5 Detrending method

Previous studies (Xu et al., 2006; Liu et al., 2010; Li et al., 2013; Huo et al., 2013) provided a simple and effective detrending method to quantify the impacts of changing meteorological variables on ETo. This method comprises of three steps: (i) removing the variation trend in different meteorological variables to make them as stationary dataset, (ii) recalculating ETo with one detrended variable while keeping the other variables unchanged, and (iii) comparing the recalculated ETo with original ETo. The contribution of changes in climatic factors to changes in ETo could be quantified by an evaluating indicator *R*:

$$R = \sum_{i=1}^{n} \frac{(ET_o^o - ET_o^R)}{ET_o^o i} \quad (17)$$

where ET_o^o and ET_o^R are original and recalculated ETo respectively, n characterize the length of the data set. $R > 0$ denotes the change of this climatic factor has positive effects to the changes in ETo; $R < 0$ denotes the change of this climatic factor has negative effects; and $R = 0$ denotes the change of this climatic factor lead to little impact on changes of ETo. The larger value of $|R|$ denotes that change of this climatic factor has greater impact on the change of ETo (Li et al., 2013).

3 Results

3.1 Climatic characteristics and trends

Meteorological data from six standard weather stations over QRB were used to calculate watershed-wide mean values (Fig. 2). The multi-year daily mean temperature was 15.6 ℃ and showed a significantly increasing trend ($p < 0.05$) since 1987 (Table 2). Mean annual precipitation was more than 1000 mm, 70 % of which occurred in the growing season (Fig. 2c). Climate in four seasons is

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-241, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 2 May 2017

characterized by: (i) T_{max} and T_{min} reached peaks in summer (Fig. 2d), (ii) WS in QRB peaked in spring and declined to a nadir in autumn (Fig. 2a), which was similar to Geng et al. (2013), (iii) maximum R_s occurred in summer (Fig. 2a), mainly caused by the longest sunshine duration, (iv) summer RH, AH and VPD were all higher than those in other seasons (Fig. 2b, c), and (v) *P* peaked in summer (Fig. 2c) mainly caused by the Asian monsoons (Liang et al., 2010).

Overall, annual ETo in QRB firstly decreased during 1961−1987, then increased during 1988−2012. The mutation point was discovered in 1987 (Table 3 and Fig. 3), which was closely related to abrupt changes in key meteorological variables that affected ETo trends (Fan et al., 2016). Therefore, we tested temporal trends for eight meteorological variables in 1961−1987 and 1988−2012 respectively (Table 1).

Spatially averaged WS showed significantly decreasing trends during 1961−1987 across all six seasons, while AH had insignificant changing trends across all seasons. The other six meteorological variables exhibited significantly changing trends across just a few seasons during 1961−1987 (Table 1). R_s in QRB have decreased significantly in summer (p < 0.05) and the whole year (p < 0.05). Slops of decreased WS ranged from −0.034 to −0.014 m s^{-1} yr^{-1}. We also found the slopes of decreased WS in spring, autumn and winter were all more than twice that in summer (Table 1), which indicated that the effects of changes in summer WS might have the minimum contribution to changes of ETo over 1961−1987. In summer, RH has a significantly (p < 0.05) increasing trend with 0.11 % yr^{-1} and VPD has a significantly (p < 0.01) decreasing trend with −0.005 kPa yr^{-1} over QRB. For air temperature variables, T_{mean} exhibited significantly (p < 0.05) decreasing trend only in winter. However, T_{max} and T_{min} might cause negative effects to changes of ETo due to the significantly decreasing trends (p < 0.05) for summer during 1961−1987 (Table 1).

Different from 1961−1987, WS showed insignificant changing trends at all six seasons in 1988−2012 (Table 1). Conversely, RH and VPD have significantly changed at all six seasons. The difference was that RH had decreasing trends ranged from −0.52 % yr^{-1} to −0.2 % yr^{-1} and VPD had increasing trends ranged from 0.007 kPa yr^{-1} to 0.014 kPa yr^{-1}. Variation tendencies of RH and VPD indicated that the environment in QRB was becoming drier in the past decades, which contributed to the increased ETo. Across vast majority of the seasons, T_{mean}, T_{max} and T_{min} have significantly increased with various slopes during 1988−2012. The largest increasing rates of T_{mean} and T_{max} were both in spring, while T_{min} has the largest increasing rate in autumn. In the four seasons of the year, smallest increasing rates of T_{mean}, T_{max} and T_{min} were all found in summer (Table 1).

3.2 Trends of ETo during 1961−1987 and 1988−2012

The MK test and linear regression both showed that the annual ETo over QRB has significantly decreased (p < 0.01) during 1961−1987, then significantly increased (p < 0.01) during 1988−2012 (Table 2 and Fig. 3f). Slopes of these trends at annual scale were both higher at 3 mm yr^{-1}. ETo of growing season occupied for nearly 70% of annual ETo in both two periods (Table 2). The growing season ETo exhibited significantly decreasing trend (p < 0.05) in 1961−1987, while it was insignificant after 1987 (Table 2 and Fig. 3e). In four seasons, mean values of ETo during 1961−1987 were very close to those in 1988−2012 respectively (Table 2). Summer ETo in 1961−1987 had the highest decreasing slope and showed significantly decreasing trend ($p < 0.01$) (Table 2 and Fig. 3b). The highest increasing rate of ETo during 1988−2012 was found in spring and it was significant ($p < 0.01$) (Table 2 and Fig. 3a).

3.3 Contributions of individual meteorological variables to the trends of ETo

3.3.1 Original and detrended meteorological variables

The linear regression detrending method based on daily meteorological data was adopted to analyze the influence of changing meteorological variables on ETo. The seasonal and annual detrended results were aggregated by the daily detrended results. Here we use Figure. 4 as an example to show obvious differences between original and detrended variables for annual scale.

In 1961−1987, only the original RH showed increasing trend which caused a lower detrended data (Fig. 4c). As negative trends were found for the other seven original variables, the drtended meteorological variables became larger. The biggest difference between original and detrended data was observed in WS in 1961−1987 (Fig. 4b). In 1988−2012, the original R_s, RH and AH showed negative trends which caused the higher detrended results (Fig. 4a, c, d). Conversely, the other five original variables in 1988−2012 all showed positive trends which caused the lower detrended results (Fig. 4b, e,

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-241, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 2 May 2017

f). It is obvious that the differences between original RH, VPD and detrended RH, VPD were much larger than the other variables during 1988−2012. Based on the example of annual data (Fig. 4) and the trends of each original meteorological variable, we could distinguish the differences between each original and detrended meteorological variable on the seasonal scale.

3.3.2 Contributions of meteorological variables to trends of ETo

The annual original ETo and recalculated ETo with detrended variables were presented as an example to show the contrast of the two datasets (Fig. 5). During 1961−1987, only the recalculated ETo with detrended AH was lower than original ETo (Fig. 5c), while recalculated ETo values using other meteorological variables were all larger (Fig. 5a, c, e, g). Differences between annual original ETo and recalculated ETo with detrended R_s, WS, AH or VPD were obviously larger than differences between annual original ETo and recalculated ones with detrended RH, T_{mean}, T_{max} or T_{min} (Fig. 5a, c, e, g). This phenomenon indicates that, in 1961−1987, the changes of first four variables had greater contributions to changes of ETo on the annual scale.

In 1988−2012, only the recalculated ETo with detrended R_s was larger than the original one (Fig. 5b). Obviously, the biggest differences were found between original ETo and the recalculated ETo with detrended RH or VPD (Fig. 5d, f). However, the smallest difference was observed between the original ETo and recalculated ETo with T_{mean}. This indicates that changes of RH and VPD in 1988−2012 had the greatest influences on changes of ETo, but changes of T_{mean} had the smallest effects on the annual scale.

The specific contributions of different variables to seasonal and annual ETo were further analyzed with the evaluating indicator *R* (Fig. 6 and Fig. 7).

In 1961−1987, the effects of decreased R_s and three temperature variables in spring were counterbalanced by the effects of changes in the other four variables, leading to little changes of ETo (Fig. 6a). In summer and autumn months, only the decreased AH brought positive effects and then offset by the negative effects of changes in the other variables. For summer, decreased R_s, VPD and increased RH were the dominant factors for the decreased ETo (Fig. 6b). For autumn, the most likely causative factors became decreased WS and VPD (Fig. 6c). The negative effect of decreased WS was the main reason for the decreased ETo in winter during 1961−1987 (Fig. 6d). In the growing season, decreased R_s, WS, VPD and increased RH were the main influencing factors in the decreased ETo (Fig. 6e).

On the annual scale, positive effect of the decreased AH has been counterbalanced by the effects of decreased R_s, WS, VPD and increased RH. Decreased T_{max} was also an important factor for negative effects (Fig. 6f). This is consistent with the conclusion drawn from Figure 5. In general, decreased R_s, VPD and increased RH mainly caused the decreased ETo in summer, while decreased WS was the main reason for decreased ETo in autumn and winter during 1961−1987. For spring, the effects of different meteorological variables offset each other and led to little changes of ETo. In growing season and the whole year, decreased ETo was greatly affected by more meteorological variables including R_s, WS,

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-241, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 2 May 2017

VPD, RH and T_{max} (Fig. 6).

During 1988−2012, decreased RH and increased VPD were the main factors for the positive trend of ETo in spring (Fig. 7a). Changes of the other six variables also contributed to the increased ETo but far less than RH and VPD. For summer and autumn, positive effects of changes in RH and VPD would offset the negative effect of changes in R_s, leading to the increased ETo (Fig. 7b, c). In winter, it was obvious that changes of RH, AH and VPD had the greatest impacts and caused the positive trend of ETo (Fig. 7d). The increased ETo in growing season and the whole year were mainly caused by the decreased RH and increased VPD (Fig. 7e, f). The decreased AH and increased air temperature were influencing factors to a lesser extent in growing season and the whole year. In general, increased VPD and decreased RH were the most influencing factors for positive trends in ETo for all seasons during 1988−2012.

4 Discussion

4.1 Temporal trends of meteorological variables

Generally speaking, R_s showed decreasing trends in the entire study period (Table 1). This is consistent with some previous studies (Liu et al., 2010; Yin et al., 2010; Li et al., 2013; Xu et al., 2015; Tabari et al., 2011a; Jhajharia et al., 2012). Irmak et al (2012) attributed this phenomenon to the increase in cloud cover and precipitation. The increase in atmospheric turbidity induced by the air pollution and dust

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-241, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 2 May 2017

storms could also reduce R_s in China (Liu 2004; Zhang et al., 2004).

Significant decreased WS was observed both on seasonal and annual scales over QRB in the past three decades. A global decrease in terrestrial WS has also been observed (McVicar et al., 2012). In China, a decline of pressure gradient, climate warming and decreasing monsoon circulation commonly reduce atmospheric circulation and WS (Zhang et al., 2009; Zhang et al., 2014).

We found significantly decreased RH during 1988−2012 (Table 1). This is consistent with what was observed over land areas globally (Simmon et al., 2010). Simmon et al. (2010) found that the slope of increasing sea surface temperatures was smaller than that of increasing land temperatures, which would limited the evapotranspiration over oceans. Furthermore, the reduced evapotranspiration supply from oceans eventually led to the decreased RH over land in recent years (Simmon et al., 2010). On a regional scale, decreased RH was corresponding with the rapid warming (Wijngaarden et al., 2005; You et al., 2015) and RH was positively correlated with the change of precipitation (Jin et al., 2009). In addition to the impacts of changing meteorological variables, population increase and more frequent human activities (such as drainage system construction, expanded cement surface) contributed to the decreased air humidity in city (Wypych, 2009). During our study period, AH presented a negative trend over QRB (Table 1), which was similar to the situation in Guizhou province of southwest China (Han et al., 2016). However, Xie et al (2014) observed an increasing AH during 1951−2002 in the flatland of Haihe River basin in northern China. Moreover, Jiang et al (2015) observed two change points in the variation tendency of AH during 1960−2011 in the northern and southern regions of Qinling Mountains. It is unclear about the causes of AH variation. Further studies are needed to explain the decreased AH over QRB.

VPD has significantly increased from 1988 to 2012 in the QRB (Table 1), which has also been observed globally (Matsoukas et al., 2011). Matsoukas et al. (2011) suggested that the global warming was an important factor for increased VPD. On a regional scale, increased VPD was also observed in Bet Dagan, Israel in summer and autumn months (Cohen et al., 2002) and at a few sites of northeast India on the annual scale (Jhajharia et al., 2012). In the Platte River basin, the increased VPD was correlated to the air temperature and precipitation to a great extent. In our study basin, the increase in VPD was the most important controlling factor on the changes of ETo during 1988–2012 and attributed to these reasons: (i) the increase in saturated vapor pressure (e_s) which was due to the warming trends and (ii) the decreased actual vapor pressure (e_a) in QRB.

This study found that increasing trend of air temperature were found in vast majority of seasons during 1988−2012 (Table 1). Warming trends are also reported in other regions in China such as the Yangtze River Delta (Cui et al., 2008), northern and southern regions of Qinling Mountains (Zhou et al., 2011), Jing River basin (Xu et al., 2015) and China as a whole (Han et al., 2013). Increasing trends of the three temperature variables had also been found in other parts of the world (Tabrai et al., 2011b; Jhajharia et al., 2012 Irmak et al., 2012; Darshana et al., 2013). Previous studies attributed the increased

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-241, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 2 May 2017

temperature variables to some reasons, for instance: global warming, increased greenhouse gases in the atmosphere (Soltani et al., 2008), expanded cloudage (Darshana et al., 2013), vast urbanization and industrialization (Tabari et al., 2011b; Roger and Pielke, 2005; Cui et al., 2008).

4.2 Temporal trends and turning points of ETo during 1961−2012

Most of the existing studies on the changing trend of ETo in China are conducted in water-shortage areas of northern China and the vast majority of these studies showed a continuous unidirectional change in ETo (Table 3). However, Xu et al. (2006) found ETo decreased significantly at annual scale during 1960−2000 at Yangtze River basin of the humid southern China. In contrast, in a short study (1971−2008), Yin et al. (2010) found an increased ETo trend in autumn over humid southeast coastal China (Table 3). Abrupt change points have also been detected in a few studies. Zhang et al. (2013) presented an upward trend of ETo from 1960, changing to a declining trend in 1992 in China. ETo in Haihe River basin of northern China, on the basis of Zhao et al.'s (2015) study, showed a decreasing trend during 1960−1989 and then increased (Table 3). Similar to this basin, Fan's et al. (2016) found an abrupt change point of annual ETo existed in 1987 over the subtropical monsoon zone (south China). Huo et al. (2013) reported that the seasonal ETo decreased from 1955 to mid-1980s and then increased in the arid region of northwest China. However, the abrupt change points appeared in different years in these studies, which were closely related to the abrupt changes in key meteorological variables which affected ETo trends (Fan et al., 2016). Our study revealed a turning point (1987) in the variation tendency of ETo during 1961−2012.

4.3 Contributions of meteorological variables to ETo trends

Many studies found decreased trends of ETo in different basins under a warming climate (Table 3). Different from these literatures, we found ETo follows the air temperature variation in this study (Table 1 and Table 2). Our analysis indicated that ETo was driven by not only air temperature but also other meteorological variables in both two periods. During 1961−1987, decreased WS was found to be the most influential factor causing negative effects on ETo in spring, autumn, winter and the whole year (Fig. 6a. c. d. f). This was consistent with some previous studies (Yin et al., 2010; Xu et al., 2015; Li et al., 2013; Chen et al., 2006; Jhajharia et al., 2012; Darshana et al., 2012). The most influential factor in the changes of ETo was decreased R_s in summer and growing season (Fig. 6b, e), the same as studies in Yunnan province of southwestern China (Fan and Thomas, 2012), subtropical and tropical regions in China (Yin et al., 2010). Decreased VPD and increased RH were also important influencing factors contributing to the decreased ETo in summer and growing season during 1961−1987 (Fig. 6b, c). The increased RH was also found to contribute to the decreased ETo in Tibetan Plateau with the study period before 2000 (Chen et al., 2006). However, this situation was opposite to some previous studies which showed decreased RH (Li et al., 2013; Liu et al., 2010), mainly because of different study periods.

During 1988−2012, the positive trends of seasonal and annual ETo were dominated by the effects of decreased RH and increased VPD (Fig. 7). In another word, the gradually drying environment in QRB

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-241, 2017
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Discussion started: 2 May 2017

was the main reason for the increased ETo during 1988−2012. This was in line with situations in Yellow River basin (Liu et al., 2010), upper basin of Heihe River (Li et al., 2013), southern Taiwan (Yu et al., 2001) and west half of Iran (Tabari et al., 2011a). For the Yangtze River basin of southern China, Sensitivity coefficients of different climatic factors ranked as: RH > R_s > T_{mean} > WS (Gong et al., 2006). However, Xu et al. (2006) found decreased R_s and WS contributed the most to the changes of ETo during 1960−2000. Fan et al. (2016) proposed that the reduction in sunshine hours was the main reason for the decreased ETo in subtropical monsoon zone of southern China during 1956−2015. It appears that the climatic controls in our study watershed are different from these general long-term patterns identified by Xu et al. (2006) and Fan et al. (2016) for humid regions. The effects of changing VPD are more pronounced during the recent 30 years since the 1980s. In other studies during recent two or three decades (Zhang et al., 2013; Yang et al., 2014; Zhao et al., 2015) (Table 3), the rapidly increased air temperature was considered to be the main reason for increased ETo. These studies were also different from our results, because they focused the effects of air temperature with little attention to the effects of the changes in VPD. Our new analysis suggested that in addition to the increase in temperature, other factors such as increased VPD and decreased RH were the main causes for the observed increase in ETo in QRB. Our findings are consistent with Kingston et al. (2009) who suggested that in addition to air temperature, other meteorological variables were important in estimating ETo.

4.4 Implication of increasing VPD and ETo for future agricultural water management

Understanding water vapor distribution under climate change and an urbanizing environment is important to quantify altered hydrological processes. Most existing studies on water vapor focus on analyzing the surface relative humidity (Simmons et al., 2010; Vincent et al., 2007; Wijngaarden and Vincent, 2005). However, Novick et al. (2016) proposed that atmospheric demand for water was directly related to the vapor pressure deficit (VPD) which also affected the surface conductance to water vapor and ET. In our study, we found sharply increased VPD after 1987, which has caused the increased ETo over QRB. Combined with higher crop coefficients, the crop water demand in growing seasons would increase with the increase in ETo (Liu et al., 2010; Vu et al., 2005). In dry seasons (Spring and Winter) when there is limited *P*, increased crop water demand aggravated water shortage and then led to serious adverse influence on food production (Fan et al., 2016). Wang et al. (2017) found technological progress such as improved irrigation systems, uses of greenhouses for growing crops and seed improvement could counterbalance the increasing crop water demand caused by the increase in ETo in China. However, in the Tibet plateau region and northeast China, the increased ETo overwhelmed the beneficial effect of technological progress, causing negative effects on crop growth (Lobell et al., 2011; Wang et al., 2017). Therefore, a drying condition and increasing ETo trend requires new management strategy for sustaining water resources in QRB.

5 Conclusions

This long-term study (1961−2012) shows that ETo over Qinhuai River Basin has changed significantly over the past 52 years: a decreasing trend during 1961–1987 and then an increasing trend during 1988−2012. Prior to 1987, decreased WS, R_s, VPD and increased relative humidity were responsible for the negative trends of ETo. The positive trends of ETo during 1988–2012 were mainly caused by effects of decreased relative humidity and increased VPD. The decreased absolute humidity and increased air temperature also contributed to the increased ETo to a lesser degree.

Paddy rice is the main crop that depends on water resources in southern China, especially in the lower Yangtze River Basin. Our study has important implications for watershed management in these paddy field-dominated regions, and similar humid regions, where actual water loss is mainly controlled by atmospheric demand. This study found an increase in ETo due to the increase in VPD in the recent decades, indicating that the water loss by evapotranspiration has been on the rise in the research watershed. Rice paddies require regular irrigation in the growing season to sustain high productivity. Therefore, despite the humid climate, an increase in irrigation water demand in the rice planting area is expected in the future. Similarly, natural wetlands that are abundant in the study region may be affected as a result of hydrological change from atmospheric drying. Our study results also have an implication to watershed energy balance since water and energy are closely coupled. Urban heat island effects in the study basin may be also aggravated with an increase in air temperature and ETo and associated hydrological changes.

Future water management must also consider the recent shifts of climatic control on the hydrological cycles. Because atmospheric demand (VPD) is a major control on potential water loss over the study region, predicting hydrological change under a changing climate must consider both air humidity and air temperature. Climate predictions from General Circulation Models (GCMs) must be assessed for their accuracy to simulate VPD in addition to air temperature and precipitation. In addition, potential ET algorithms that are often embedded in watershed hydrological models must include VPD as a major input variable to fully account for atmospheric water demand and actual ET.

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Table 1. Trends of key meteorological variables in Qinhuai River Basin during 1961−1987 and 1988−2012

Periods	Variables	Spring	Summer	Autumn	Winter	Growing season	Annual
1961−1987	Rs ($MJ\ m^{-2}\ d^{-1}$)	-	−0.061*	-	-	-	−0.027*
	WS ($m\ s^{-1}$)	0.031***	−0.014*	0.032***	0.034***	−0.025***	0.027***
	RH (%)	-	0.11*	-	-	-	-
	AH ($g\ m^{3}$)	-	-	-	-	-	-
	VPD (kpa)	-	−0.005**	-	-	-	-
	T_{mean} (℃)	-	-	-	−0.043*	-	-
	T_{max} (℃)	-	−0.054**	-	-	−0.026+	−0.029*
	T_{min} (℃)	-	−0.029*	-	-	-	-
1988−2012	Rs ($MJ\ m^{-2}\ d^{-1}$)	0.048+	−0.073+	−0.051*	-	−0.049+	-
	WS ($m\ s^{-1}$)	-	-	-	-	-	-
	RH (%)	−0.52***	−0.31***	−0.20*	−0.28***	−0.33***	−0.38***
	AH ($g\ m^{3}$)	-	−0.046*	-	−0.024+	−0.030+	-
	VPD (kpa)	0.014***	0.014***	0.007***	0.003*	0.013***	0.010***
	T_{mean} (℃)	0.079**	0.038+	0.058**	-	0.045**	0.039*
	T_{max} (℃)	0.114**	0.037+	-	-	0.048**	0.038+
	T_{min} (℃)	0.056+	0.045*	0.084**	-	0.055***	0.041*

***, **, *, and + means the significance level of 0.001,0.01.0.05 and 0.1 respectively. Meteorological variables are solar radiation (Rs), wind speed (WS), relative humidity (RH), absolute humidity (AH), vapor pressure deficit (VPD), mean temperature (T_{mean}), maximum temperature (T_{max}), and minimum temperature (T_{min})

Table 2. Mean seasonal and annual ETo estimated by P−M model; trends of seasonal and annual ETo obtained through Mann-Kendall test during 1961−1987 and 1988−2012

Season	1961−1987			1988−2012		
	ETo (mm)	Trend	β (mm yr^{-1})	ETo (mm)	Trend	β (mm yr^{-1})
Spring	266	↓	−0.04	280	↑**	2.55
Summer	404	↓**	−2.05	391	↑	0.16
Autumn	206	↓	−0.57	211	↑$^{+}$	0.38
Winter	102	↓$^{+}$	−0.37	100	↑*	0.56
Growing season	685	↓*	−2.53	679	↑	1.09
Annual	980	↓**	−3.82	982	↑**	3.16

***, **, *, $^{+}$ means the significance level of 0.001,0.01.0.05 and 0.1. β is the estimated magnitude of slopes of ETo trends. $\beta > 0$ represents an increasing trend (↑); $\beta < 0$ represents a decreasing trend (↓).

655 **Table 3.** The trends of ETo and dominant meteorological variables in different basins of China

Region	Periods	Trends of ETo	Dominant meteorological variables	References
China	1971−2008	Decreased in 1971−2008	Declining wind speed and decreasing sunshine duration	Yin et al. (2010)
China	1960−2011	Decreased in1960−1992	Before 1992: decrease in solar radiation in humid region; decrease in wind speed in arid and semi-arid/semi-humid region	Zhang et al. (2013)
		Increased in 1993−2011	After 1992: rapidly increasing temperature in all three regions	
Yangtze River Basin	1960−2000	Decreased	Decrease in net total radiation and wind speed	Xu et al. (2006)
Yellow River Basin	1961−2006	Increased in the whole basin	Increasing air temperature and decreasing relative humidity	Liu et al. (2010)
Jing River Basin	1960−2005	Decreased in spring, summer and winter; Increased in autumn	Spring, summer and winter: decrease in wind speed; Autumn: increase in maximum temperature;	Xu et al. (2015)
Taohe River Basin	1981−2010	Increased	Increasing air temperature and net total radiation	Yang et al. (2014)
Hai River Basin	1960−2012	Decreased in 1960−1989	Before 1989: decrease in solar radiation	Zhao et al. (2015)
		Increased in 1990−2012	After 1989: global warming	
Qinhuai River Bain	1961−2012	Decreased in 1961−1987; Increased in 1988−2012	Before 1987: decrease in wind speed, solar radiation and VPD; After 1987: rapidly increasing VPD and increasing T_{max}	This study

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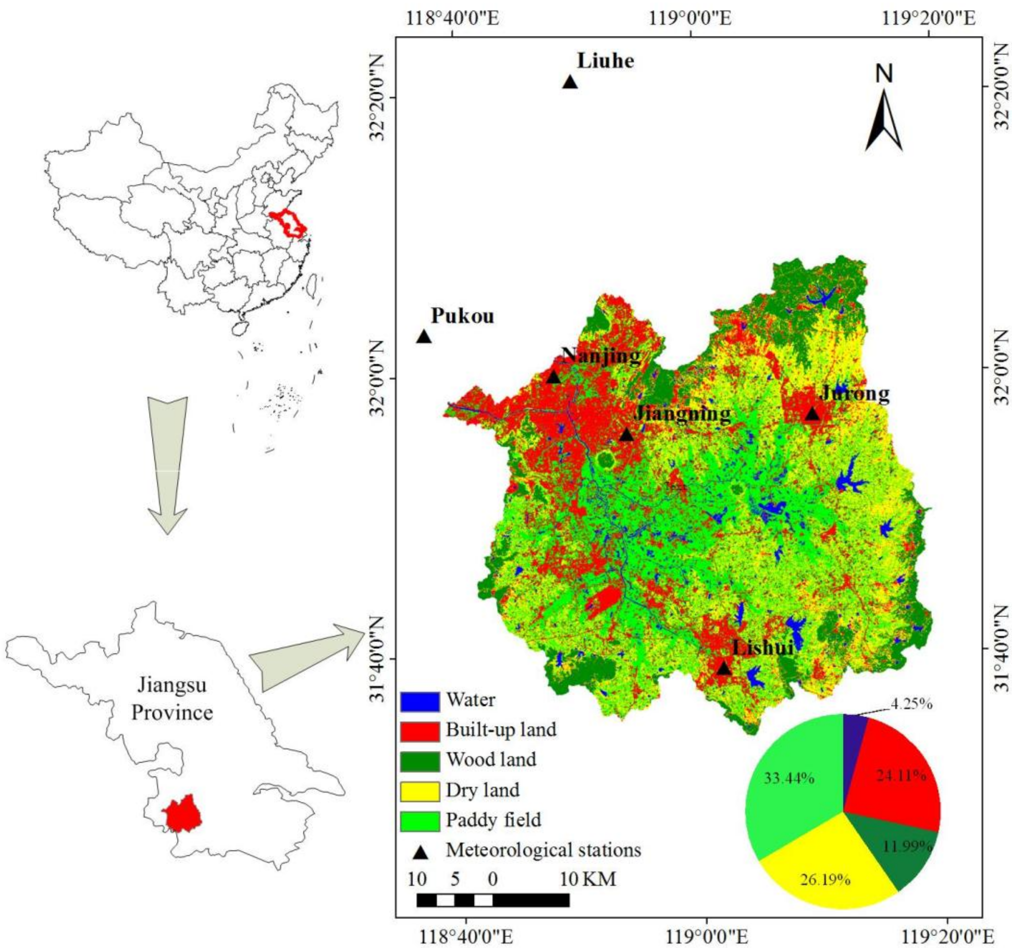
Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-241, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 2 May 2017



665 **Fig. 1.** Watershed location, land use and land cover (2013), and weather stations around the Qinhuai River Basin. The insert pie chart indicates the proportion of five land use area to total area.

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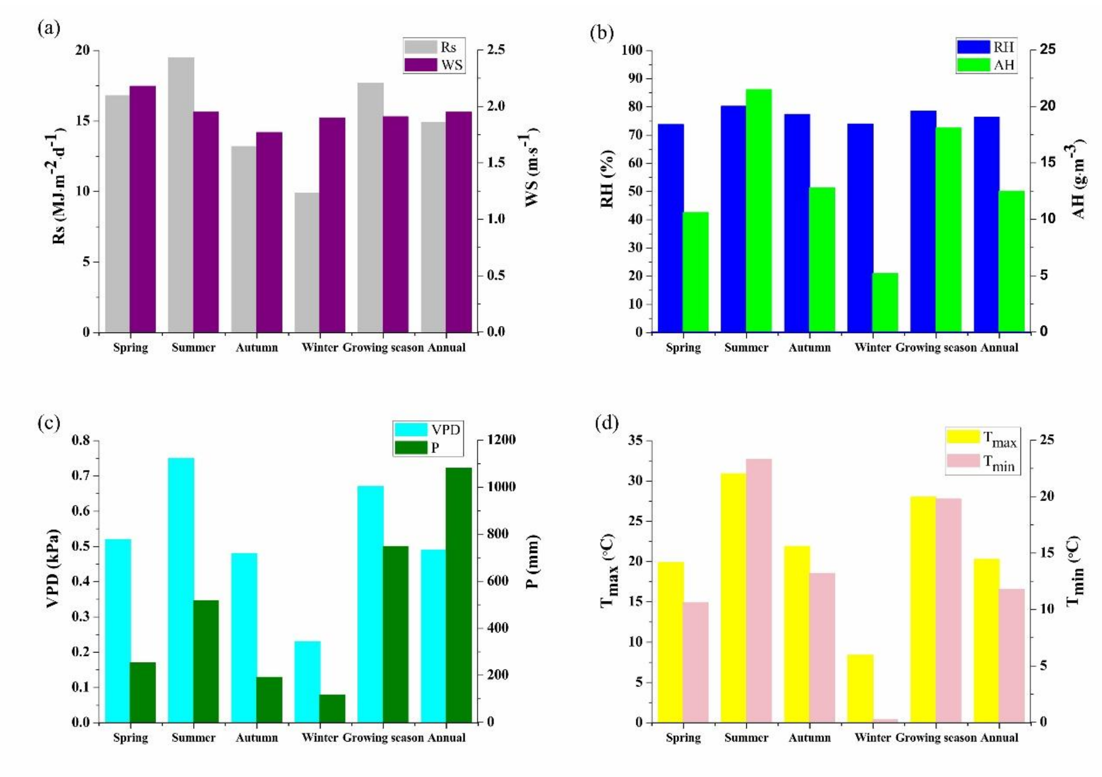

Fig. 2. Basic meteorological information in Qinhuai River basin during 1961−2012: (**a**) Solar radiation (R_s) and Wind speed (WS); (**b**) Relative humidity (RH) and Absolute humidity (AH); (**c**) Vapor pressure deficit (VPD) and Precipitation (p); and (**d**) Maximum temperature (T_{max}) and Minimum temperature (T_{min}).

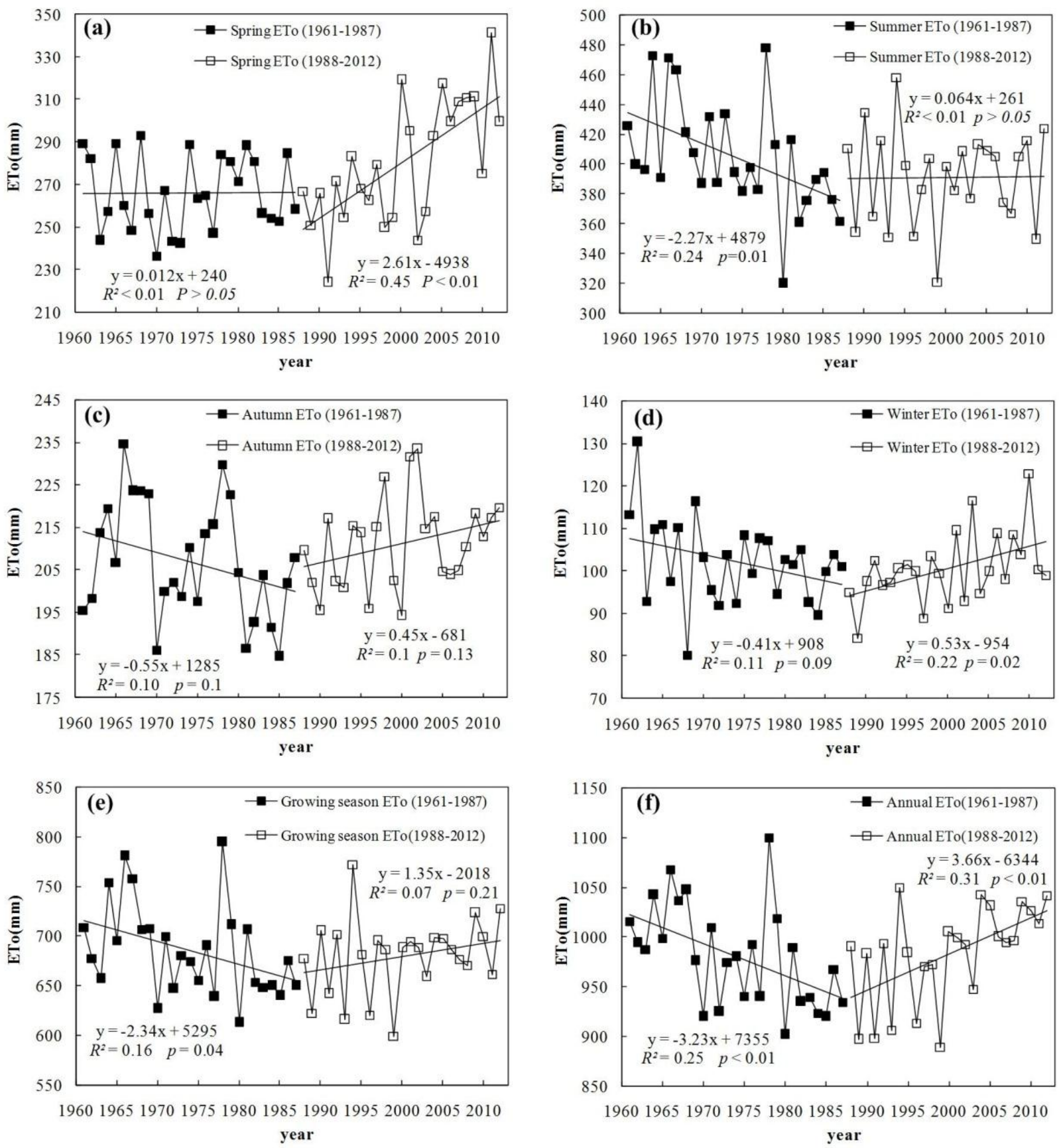

Fig. 3. Linear fitted trends of (**a**) spring; (**b**) summer; (**c**) autumn; (**d**) winter; (**e**) growing season; and (**f**) annual ETo during 1961–1987 and 1988–2012.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-241, 2017
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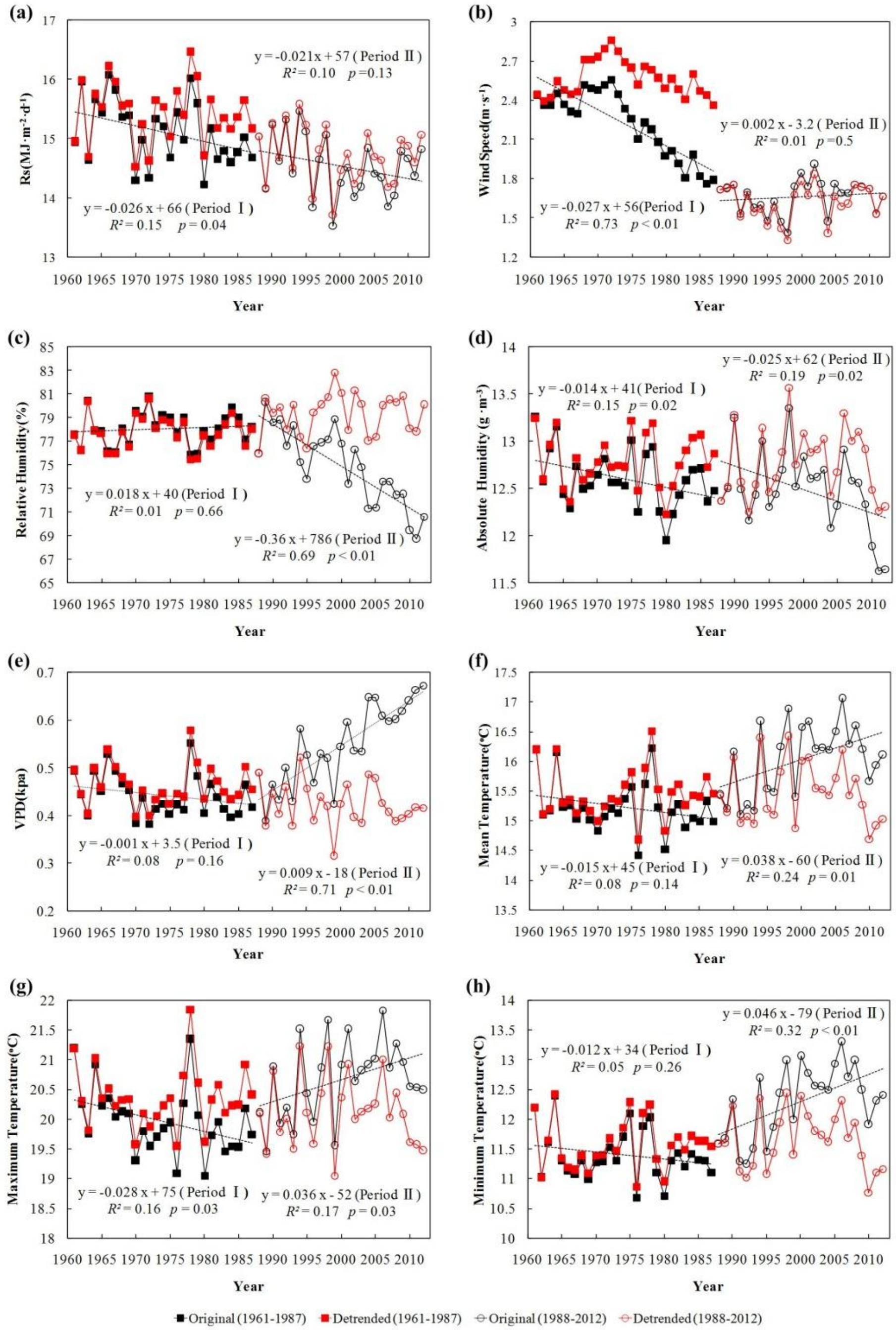

700 **Fig. 4.**The annual original and detrended meteorological variables (**a**) Solar radiation (R_s); (**b**) Wind speed (WS); (**c**)Relative humidity (RH); (**d**) Absolute humidity (AH); (**e**) Vapor pressure deficit (VPD); (**f**) Mean temperature (T_{mean}); (**g**) Maximum temperature (T_{max}); and (**h**) Minimum temperature (T_{min}) for Qinhuai River basin by using detrending method (Period I represents 1961−1987 and Period II represents 1988−2012).

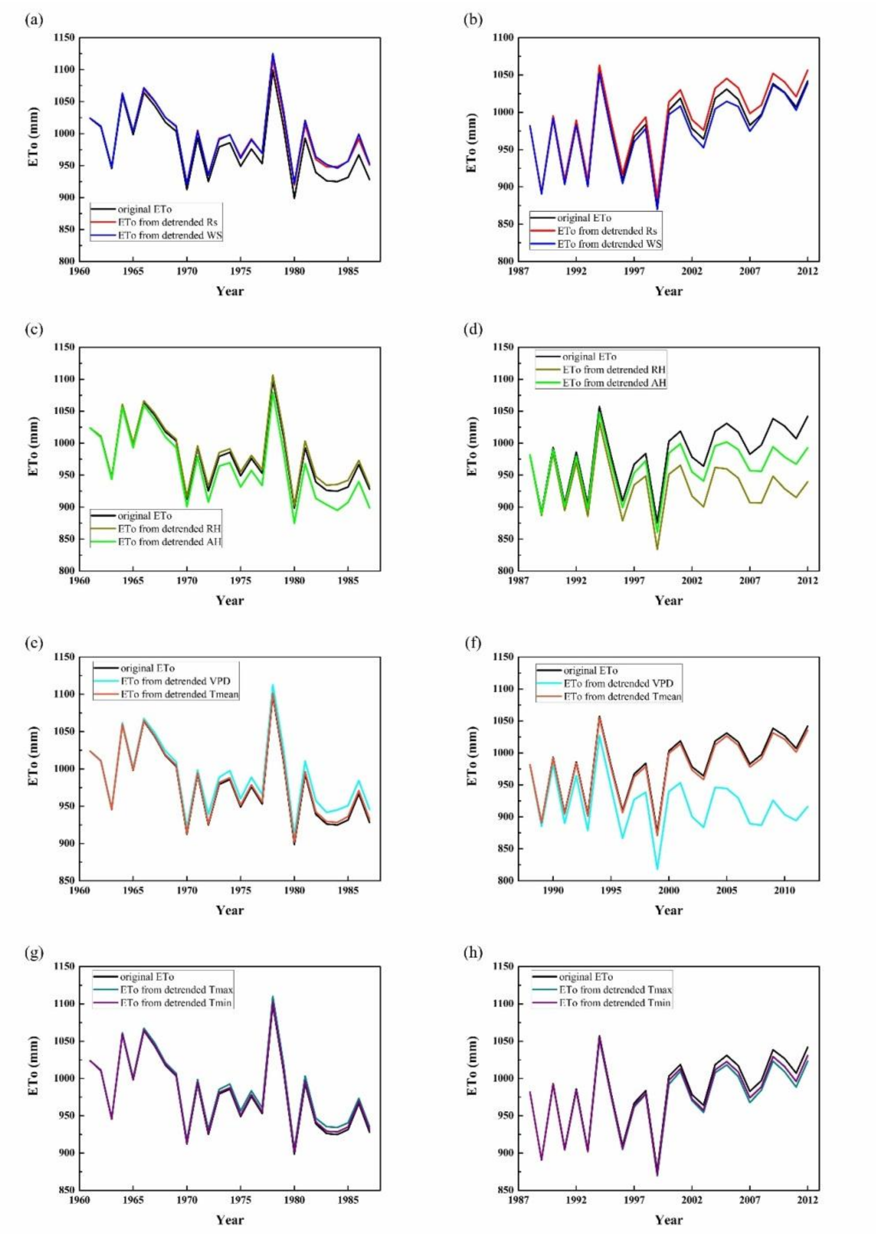

Fig. 5. The original and recalculated annual ETo for Qinhuai River basin with detrended meteorological variables during 1960−1987 (**a**) Solar radiation (R_s) and Wind speed (WS); (**c**) Relative humidity (RH) and Absolute humidity (AH); (**e**) Vapor pressure deficit (VPD) and Mean temperature (T_{mean}); (**g**) Maximum temperature (T_{max}) and Minimum temperature (T_{min}); and 1988−2012 (**b**) Solar radiation (R_s) and Wind speed (WS); (**d**) Relative humidity (RH) and Absolute humidity (AH); (**f**) Vapor pressure deficit (VPD) and Mean temperature (T_{mean}); and (**h**) Maximum temperature (T_{max}) and Minimum temperature (T_{min}).

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-241, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
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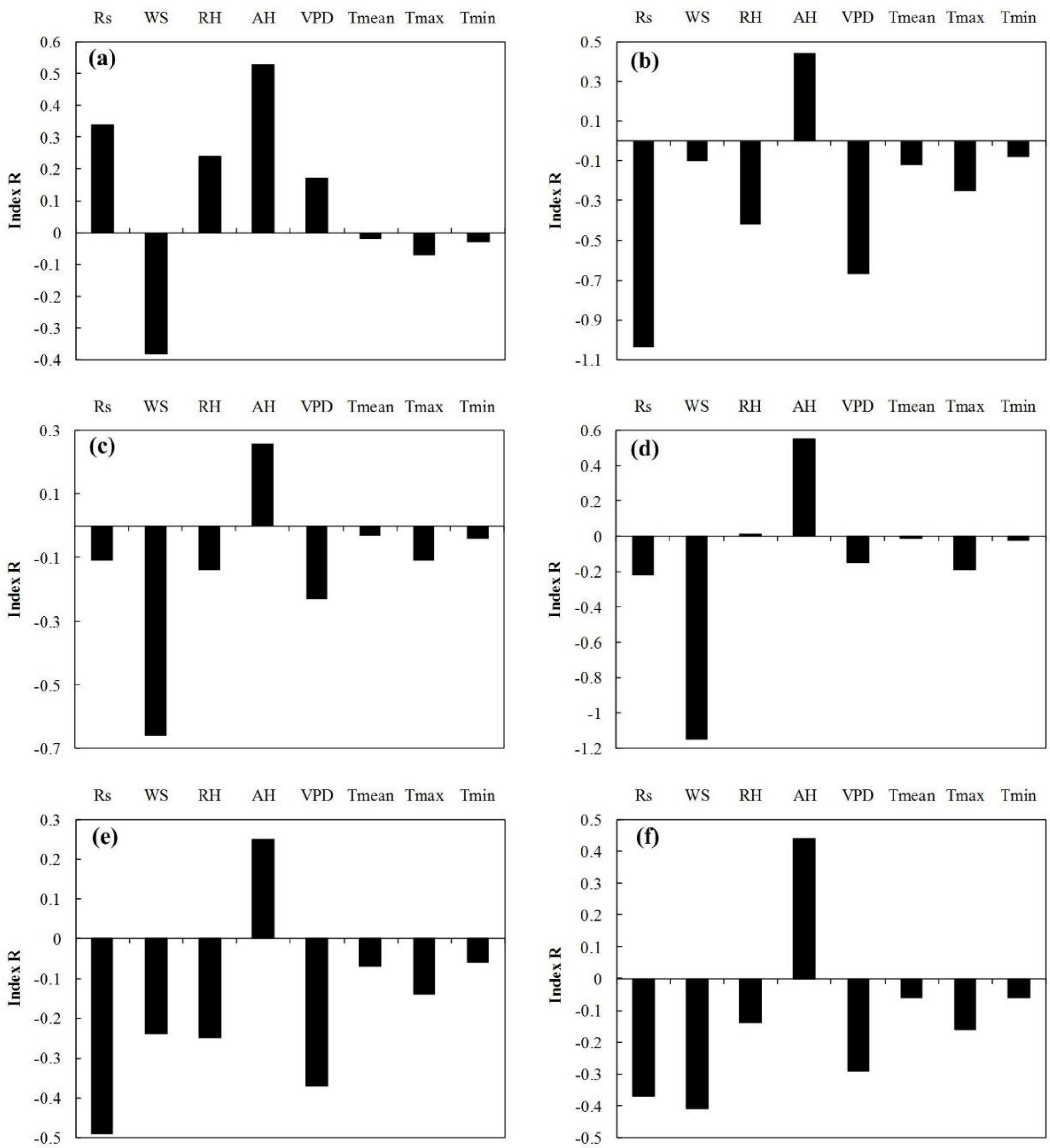

Fig. 6. Comparisons of indicator R for identifying the contributions of trends in meteorological variables to trends in ETo in (**a**) spring; (**b**) summer; (**c**) autumn; (**d**) winter; (**e**) growing season; and (**f**) annual during 1961−1987. Positive R values indicate positive effects and negative values indicate negative effects; the greater of the absolute R values indicate greater contributions to changes in ETo.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-241, 2017
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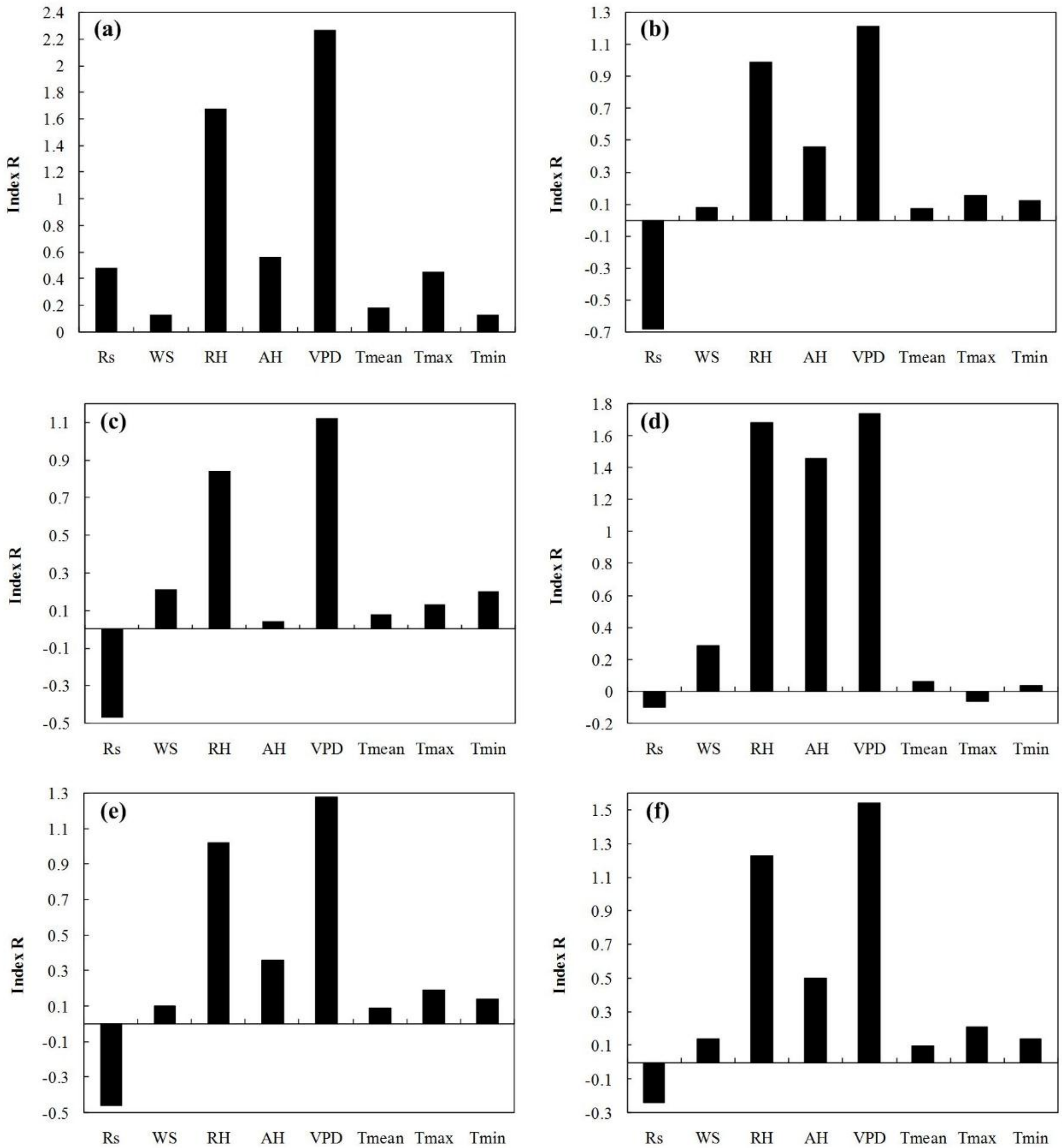

Fig. 7. Comparisons of evaluating indicator R for identifying the contributions of trends in meteorological variables to trends in ETo in (**a**) spring; (**b**) summer; (**c**) autumn; (**d**) winter; (**e**) growing season; and (**f**) annual during 1988−2012. Positive R values indicate positive effects and negative values indicate negative effects; the greater of the absolute R values indicate greater contributions to changes in ETo.