Spatiotemporal Characteristics of Reference Evapotranspiration and Its Sensitivity Coefficients to Climate Factors in Huang-Huai-Hai Plain, China

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Abstract

Climate change will have important implications in water shore regions, such as Huang-Huai-Hai (3H) plain, where expected warmer and drier conditions might augment crop water demand. Sensitivity analysis is important in understanding the relative importance of climatic variables to the variation in reference evapotranspiration ($ET_0$). In this study, the 51-yr $ET_0$ during winter wheat and summer maize growing season were calculated from a data set of daily climate variables in 40 meteorological stations. Sensitivity maps for key climate variables were estimated according to Kriging method and the spatial pattern of sensitivity coefficients for these key variables was plotted. In addition, the slopes of the linear regression lines for sensitivity coefficients were obtained. Results showed that $ET_0$ during winter wheat growing season accounted for the largest proportion of annual $ET_0$, due to its long phenological days, while $ET_0$ was detected to decrease significantly with the magnitude of 0.5 mm yr$^{-1}$ in summer maize growing season. Solar radiation is considered to be the most sensitive and primarily controlling variable for negative trend in $ET_0$ for summer maize season, and higher sensitive coefficient value of $ET_0$ to solar radiation and temperature were detected in east part and southwest part of 3H plain respectively. Relative humidity was demonstrated as the most sensitive factor for $ET_0$ in winter wheat growing season and declining relativity humidity also primarily controlled a negative trend in $ET_0$, furthermore the sensitivity coefficient to relative humidity increased from west to southeast. The eight sensitivity centrals were all found located in Shandong Province. These $ET_0$ along with its sensitivity maps under winter wheat-summer maize rotation system can be applied to predict the agricultural water demand and will assist water resources planning and management for this region.

Key words: $ET_0$, spatial distribution, temporal trends, sensitivity coefficient, 3H plain

INTRODUCTION

A global change in the main meteorological variables has been observed in the last decades. According to the IPCC report, in recent 100 years (1906-2005), the global temperature has raised by 0.74°C (IPCC 2007), and it is likely to continue in the 21st century, and caused changes in the hydrological cycle by affecting precipitation and evaporation (Huntington 2006). The climate change with the characteristic of global warming has become a hot spot of research in field of water
resources, agriculture, ecology, and other disciplines. Changes in climatic elements such as temperature, precipitation, radiation, humidity, and wind speed could have profound implications for hydrologic processes (McKenney and Rosenberg 1993). Previous studies have focused attention on two aspects, followed by the quantification of climate changes (Türkeş et al. 2002; Wu et al. 2006; Toreti and Desiato 2008; de Luis et al. 2009; El Kenawy et al. 2007) and relative humidity (Gonzalez et al. 2011c) and the assessment of the impacts of those changes on different fields (Walther et al. 2002; Izaurralde et al. 2003; Gong et al. 2006; Mizyed 2009).

As one of the important parameters of the hydrologic cycle, reference crop evapotranspiration ($ET_0$) plays a key role in estimating and predicting actual crop evapotranspiration, water management, establishing irrigation scheme and other practice of agricultural production. $ET_0$ refers to the crop evapotranspiration in the open short grass land where the soil moisture is adequate, ground is completely covered, and grass grew normally with the similar height (grass height is about 8-15 cm). $ET_0$ is an integrated climate parameter that gives a measure of the evaporation demand of the air. Several researches have pointed out that $ET_0$ is expected to increase with temperature rise (McNulty et al. 1997; Goyal 2004). However, decreasing trends of $ET_0$ were found in some areas of China (Thomas 2000; Shenbin et al. 2006; Wang et al. 2007), India (Chattopadhyay and Hulme 1997), USA (Hobbins et al. 2004), and Australia (Roderick and Farquhar 2004). Besides, $ET_0$ is essentially dependent on four meteorological variables: air temperature, solar radiation, relative humidity and wind speed (Allen et al. 1998). One or more of those four meteorological variables can be taken into account, depending on the $ET_0$ calculation method selected. The main advantage of the Penman-Menteith approach is that it takes into account the most significant variables, so that the influence of each of them can be analyzed, physically based equations requiring daily data for temperature and relative humidity of the air, solar radiation and wind speed (Allen et al. 1998).

To understand the relative importance of climatic variables in the Penman-Menteith formulation, a sensitivity analysis is required and the results from sensitivity analysis are of vital significance for determining the effect of climate change on $ET_0$. Several papers have carried out sensitivity analysis of $ET_0$ to meteorological data in different climates (Rana and Katerji 1998; Goyal 2004; Irmak et al. 2006), but they restricted to a single station. Furthermore, what has been reported to be the most effective variable detected is wind speed (Cohen et al. 2002; Wang et al. 2007; Todisco and Vergni 2008), solar radiation (Gao et al. 2006; Wang et al. 2007) and relative humidity (Gong et al. 2006) in other papers, however, they almost restricted to monthly, seasonal or annual $ET_0$. Liu Y et al. (2010) reported the annual $ET_0$ and its constituents ($ET_{rad}$ and $ET_{aero}$) were significantly declined and that the highest $ET_0$ and $ET_{rad}$ were in summer, the lowest in winter, while the spring $ET_{aero}$ value was the highest across the North China Plain (NCP). Song et al. (2010) also reported that for the whole NCP, annual $ET_0$ showed a statistically significant decrease of 11.92 mm per decade over the 46 years of data collection and that the decreasing net radiation and wind speed had a bigger impact on $ET_0$ rates than the increases observed by the maximum and minimum temperatures. However, studies about sensitivity analysis of $ET_0$ during typical crop growing season and its variation trend are rarely seen. The objectives of this study were (1) to investigate the trends for $ET_0$ in Huang-Huai-Hai (3H) plain in the past 51 years, (2) to evaluate the major factors related to the change in $ET_0$; and (3) to develop the temporal variations of climatology sensitivity coefficients for different crops (winter wheat and summer maize), in an attempt to understand the relative roles of main climatic variables for winter wheat and summer maize.

RESULTS

Variation of $ET_0$

Investigation of trends and persistence of historical meteorological data is helpful in understanding the status of $ET_0$. We performed a comparison of $ET_0$ for winter wheat and summer maize estimated using the FAO-56 Penman-Monteith formulation. As described in Table 1, average annual $ET_0$ was 1037.7 mm, with maximum value 1155.5 mm, and minimum value
931.8 mm. Statistically significant decreasing trend at significance level of \( P<0.01 \) were found in the analysis of annual \( ET_0 \) with slope of -1.3 mm yr\(^{-1}\). \( ET_0 \) in winter wheat growing season was detected with higher value compared with \( ET_0 \) in summer maize growing season. A significant trend was found (\( P<0.01 \)) for \( ET_0 \) in summer maize growing season, with a decreasing trend of -0.8 mm yr\(^{-1}\), lower than the decreasing tendency of annual \( ET_0 \).

Table 1  Annual variation tendency and statistics of \( ET_0 \) in study area

<table>
<thead>
<tr>
<th>Year</th>
<th>Average ( ET_0 ) (mm)</th>
<th>Maximum ( ET_0 ) (mm)</th>
<th>Minimum ( ET_0 ) (mm)</th>
<th>Slope (mm yr(^{-1}))</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>1037.7</td>
<td>1155.5</td>
<td>931.8</td>
<td>-1.3</td>
<td>0.39**</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>682.2</td>
<td>765.8</td>
<td>591.5</td>
<td>-0.5</td>
<td>0.29</td>
</tr>
<tr>
<td>Summer maize</td>
<td>355.5</td>
<td>417.8</td>
<td>306.4</td>
<td>-0.8</td>
<td>0.54**</td>
</tr>
</tbody>
</table>

** represents linear coefficients significant at \( P<0.01 \). The same as below.

Using the Penman-Menteith equation, \( ET_0 \) was calculated in 40 stations from 1961 to 2011. A large spatial variability was found for \( ET_0 \) in winter wheat and summer maize growing season in 3H plain and different trends were detected in study area. \( ET_0 \) in winter wheat growing season was higher in the central part than in southern and northern parts as described in Fig. 1. Significant tendency was detected for \( ET_0 \) in 23 stations, among which \( ET_0 \) in 17 stations decreased and was mainly located in Shandong and Henan provinces, while \( ET_0 \) in 6 stations increased and was mainly located in Hebei Province. On the other hand, a downward trend in \( ET_0 \) in summer maize growing season was detected from east to west across the study area. \( ET_0 \) was observed to decrease significantly in around 24 stations, which mainly located in Henan Province and north part of Anhui Province.

Variation of the sensitivity coefficients

Slopes of the linear regression lines for sensitivity coefficients are listed in Table 2, and it was found that the most effective meteorological factor impacting \( ET_0 \) varied with region and season. \( ET_0 \) in summer maize growing season showed more sensitive to temperature and solar radiation, since the sensitivity coefficients of temperature \((S_T)\) and sensitivity coefficients of solar radiation \((S_{RS})\) in summer maize growing season were bigger than that in winter wheat growing season. Solar radiation was the dominant factor to \( ET_0 \) in summer maize growing season, for its sensitivity coefficient value was 0.677. Trends of \( S_T \) are negative in the time series analysis, which means that the negative influence in \( ET_0 \) got bigger in the 51 yr, combining with the negative value of \( S_T \). Compared with \( S_T \) in summer maize growing season, changes of \( S_{RS} \) was detected with more obvious tendency, with a trend of -0.089 per decade at the significant level of \( P<0.01 \), which means that changes in solar radiation contributed less to the fluctuation of \( ET_0 \) in summer maize growing season in the 51 yr. RH was demonstrated as the most sensitive factor for \( ET_0 \) in winter wheat growing season, with the sensitivity coefficients of relative humidity \((S_{RH})\) value of -1.159,
followed by solar radiation, temperature and wind speed. Obvious increasing trend was detected in $S_{RH}$ in winter wheat growing season, with a slope of 0.071 per decade. However, influence of relative humidity to $ET_0$ in winter wheat growing season had get to be smaller, because of the negative value of $S_{RH}$ in winter wheat growing season.

Sensitivity surfaces for climate variables in growing period of winter wheat and summer maize are presented in Figs. 2 and 3. These maps are obtained from the interpolated meteorological surfaces according to Krigeing method in Geostatistical analysis module. The spatial pattern of sensitivity coefficients for $S_{RS}$, $S_{RH}$, $S_T$ and wind speed ($S_{WS}$) during winter wheat and summer maize was plotted in these maps. Spatial pattern of sensitivity coefficients of $ET_0$ were mapped in winter wheat and summer maize growing season in 3H plain respectively, and tendency of sensitivity coefficients has been calculated in every single station, in order to detect their significantly change in time series. Results showed that the $S_T$ decreased from north to south in winter wheat growing season, which means that changes in temperature may lead to greater decrease of $ET_0$ in winter wheat growing season in the south part of the study area. 18 stations had been detected with significant decreasing trend ($P<0.01$), mainly located in Henan and Hebei provinces. Higher value was detected in $S_{RS}$ in the north part of 3H plain. $S_{RS}$ in 9 stations decreased at the significance level of $P<0.01$, and the decreasing tendency was more obvious in Hebei and Anhui provinces. While $S_{RS}$ in the other 9 stations increased, more slow trend mainly located in Hebei and Jiangsu provinces. $S_{WS}$ in winter wheat growing season showed opposite change pattern to $S_{ws}$, with higher value detected in the south part. More sharply decreasing tendency was located in Hebei Province and northern part of Anhui Province, and more sharply increasing trend mainly located in Henan and northern part of Jiangsu provinces. $S_{RH}$ increased from west to southeast, with 29 stations significantly increased, especially in Hebei and Henan provinces. $ET_0$ in summer maize growing season was more sensitive to temperature fluctuating in east part of 3H plain than in west part. $S_T$ in 26 stations significantly increased, especially in Hebei and Henan provinces. $S_{RS}$ increased from northeast to southwest in summer maize growing season, which means that changes in solar radiation may lead greater decrease of $ET_0$ in southwest part of study area. 26 stations had been detected with significant decreasing trend ($P<0.01$), more obvious decreasing tendency of $S_{RS}$ mainly located in Hebei and Shandong provinces. Higher value was detected in $S_{WS}$ in the north part of 3H plain. $S_{WS}$ in 26 stations increased at the significance level of $P<0.01$, and $S_{WS}$ in summer maize growing season increased more sharply in Hebei Province. Higher value was detected in $S_{RH}$ in summer maize growing season in the northwest of 3H plain. $S_{RH}$ in 12 stations significantly increased, which mainly located in Henan Province, while there were also 5 stations detected with decreasing tendency in $S_{RH}$, which mainly located in Hebei Province.

**Table 2** Annual variation tendency and statistics of sensitivity coefficient of $ET_0$ in 3H plain

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Slope (per decade)</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{ET}$</td>
<td>Annual</td>
<td>-0.267</td>
<td>-0.132</td>
<td>-0.331</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>Winter wheat</td>
<td>-0.159</td>
<td>0.009</td>
<td>-0.234</td>
<td>-0.014</td>
</tr>
<tr>
<td></td>
<td>Summer maize</td>
<td>-0.592</td>
<td>-0.535</td>
<td>-0.679</td>
<td>-0.011</td>
</tr>
<tr>
<td>$S_{RS}$</td>
<td>Annual</td>
<td>0.428</td>
<td>0.469</td>
<td>0.376</td>
<td>-0.005</td>
</tr>
<tr>
<td></td>
<td>Winter wheat</td>
<td>0.345</td>
<td>0.391</td>
<td>0.296</td>
<td>-0.004</td>
</tr>
<tr>
<td></td>
<td>Summer maize</td>
<td>0.677</td>
<td>0.709</td>
<td>0.614</td>
<td>-0.089</td>
</tr>
<tr>
<td>$S_{WS}$</td>
<td>Annual</td>
<td>0.154</td>
<td>0.214</td>
<td>0.083</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>Winter wheat</td>
<td>0.186</td>
<td>0.261</td>
<td>0.101</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>Summer maize</td>
<td>0.058</td>
<td>0.101</td>
<td>0.027</td>
<td>0.007</td>
</tr>
<tr>
<td>$S_{RH}$</td>
<td>Annual</td>
<td>-1.189</td>
<td>-0.665</td>
<td>-2.121</td>
<td>0.080</td>
</tr>
<tr>
<td></td>
<td>Winter wheat</td>
<td>-1.159</td>
<td>-0.634</td>
<td>-2.079</td>
<td>0.071</td>
</tr>
<tr>
<td></td>
<td>Summer maize</td>
<td>-0.030</td>
<td>-0.020</td>
<td>-0.043</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Sensitivity coefficients for mean temperature ($S_T$), solar radiation ($S_{RS}$), wind speed ($S_{WS}$), relative humidity ($S_{RH}$). $^*$ represents linear coefficients significant at $P<0.05$. The same as below.

Sensitivity central of $ET_0$

Sensitivity centrals of $ET_0$ were calculated based on the data set of sensitivity coefficient in 40 stations in order to better understand the characteristics and spatial differentiation of sensitivity coefficients for $ET_0$ in winter wheat and summer maize growing season. It can be seen from Fig. 4 that the eight sensitivity centrals (including $S_T$, $S_{RS}$, $S_{WS}$ and $S_{RH}$ of $ET_0$ in winter wheat growing season, and $S_T$, $S_{RS}$, $S_{WS}$ and
S\textsubscript{RH} of \(ET_0\) in summer maize growing season) were all located in Shandong Province. Sensitivity centrals of \(S_T\), \(S_{RS}\), \(S_{WS}\) and \(S_{RH}\) of \(ET_0\) in winter wheat growing season located in Jiaxiang, Dongping and Wenshang counties in Shandong Province respectively, while sensitivity centrals of \(S_T\), \(S_{RS}\), \(S_{WS}\) and \(S_{RH}\) of \(ET_0\) in summer maize growing season located in Wenshang, Wenshang, Pingyin and Yanzhou counties. Sensitivity centrals of \(S_{RS}\) in summer maize growing season and in winter wheat growing season showed the farthest distance (around 33.6 km), followed by \(S_{RH}\), \(S_{WS}\) and \(S_T\).

**\(ET_0\) regional response to climate change**

Although sensitivity analysis aims to identify the most sensitive variable to \(ET_0\) during winter wheat and summer maize growing season, further study need to be conducted for \(ET_0\) with the purpose of finding out controlling factors because of variation in climatic variables. The tendency and magnitude of climate variables and relationships between \(ET_0\) and \(T\), \(WS\), \(RH\) and \(RS\) in winter wheat and summer maize growing seasons are presented in Table 3. As described, climate variables significantly changed in the past 51 yr except relative humidity in summer maize growing season, and maximum magnitude was all found in winter wheat growing season. As for winter wheat growing season, the maximum value was detected for correlation coefficient of relative humidity, that is to say, the declining relative humidity also primarily controlled a negative trend in \(ET_0\).
while the primarily controlling variable turned to be solar radiation in summer maize season, followed by wind speed. Solar radiation also was the primarily controlling variable for negative trend in annual $ET_0$, followed by relative humidity, mean temperature and wind speed. These findings indicate that each climate variable has an important role to play in the trend and magnitude and their roles change with regional characteristics. Thus, only one or two meteorological variables cannot be responsible for the trend and magnitude of $ET_0$ and they all need be accounted for in a combination-based energy balance equations when used in climate change studies.

**DISCUSSION**

$ET_0$ during winter wheat growing season accounted for the largest proportion of annual $ET_0$ due to its...
long phenological days, while it is characterized by significantly decreasing with the magnitude of 0.5 mm yr$^{-1}$ in summer maize growing season. Similar results have been reported for Wuqiao Agricultural Experiment Station in North China plain by Kong (2012). Furthermore, a significant ET$_0$ decrease was found in analysis of annual ET$_0$. This is in agreement with some other researches (Thomas 2000; Shenbin et al. 2006; Wang et al. 2007; Liu Y et al. 2010; Song et al. 2010), which have pointed in this direction, although ET$_0$ is expected to increase in the next years on a par with temperature rise according to climate change model predictions. For the agriculture regions of water shortage, such as 3H plain, relative humidity is the most sensitive variable in the whole winter wheat-summer maize rotation system. This is partially agreed by Chattopadhyay and Hulme (1997), who pointed out that relative humidity is a major limiting factor to ET$_0$ if warming is accompanied by higher humidity. However, this contrasts with the result pointed out by Gao et al. (2006) and Wang et al. (2007). They pointed out that solar radiation reduction along with wind speed was the main contributing variables. As for summer maize growing season, solar radiation is the most sensitive and primarily controlling variable for negative trend in ET$_0$, similar to the results reported by Bo et al. (2011).

The fluctuation of ET$_0$ is expected to have important consequences due to its overlap with the precipitation changes. This will lead to a corresponding changes of irrigation, or a necessity to modify the present cropping patterns and agronomic techniques (Olesen and Bindi 2002; Vergni and Todisco 2011). From ET$_0$ estimates, and using adequate crop coefficients (Doorenbos and Pruitt 1975; Allen et al. 1998), irrigation schedules can be defined. In addition, it could be of great help to simulate optimization procedures under water restrictions. With the results provided in this study, agronomic effects due to changes in ET$_0$ in winter wheat-summer maize rotation system could be inferred for irrigated agriculture in 3H plain. Thus, the changes in ET$_0$ would redefine irrigation requirements if crop coefficient curves were not affected by the weather conditions. However, a marked inter-annual and inter-decadal variation of drought occurred in North China according to the revised Palmer drought severity index (PDSI) and there have been more drought years in North China since 1970 (Wei et al. 2003). It is necessary to develop feasible late sowing, straw mulching, regulated deficit irrigation and soil water storage and preservation especially for winter wheat in North China. In addition, it would be expected for the crop cycle to modify due to changes of weather and crop water requirement. In Spain, Döll (2002) has estimated a decrease in irrigation requirements in 2020 due to the possibility of sowing earlier in time when higher temperature is more favorable. Finally, it is difficult to quantify the influence of the detected changes on soil moist in the region, especially when ET$_0$ decreases with the absence of trend in precipitation. This would tend to increase aquifer recharge, being not well in agreement with the reported drying trend in this region (Liu et al. 2011). It is therefore necessary to model the aquifers behavior in order to understand the possible impacts of crop actual evapotranspiration and of future climate change on water resources.

**CONCLUSION**

The 51-yr ET$_0$ during winter wheat and summer maize growing season for 3H plain were calculated from a data set of daily climate variables in 40 meteorological stations. Sensitivity maps for key climate variables in winter wheat and summer maize season were estimated from the interpolated meteorological surfaces according to Kriging method and the spatial pattern variability in sensitivity coefficients because these key variables was plotted in these maps. In addition, the slopes of the linear regression lines for sensitivity coefficients were described in Table 2. These ET$_0$ along with its sensitivity maps under winter

**Table 3** The trend and correlation coefficients between annual ET$_0$ with key climatic variables in 3H plain

<table>
<thead>
<tr>
<th>Trend</th>
<th>Mean temperature (°C per decade)</th>
<th>Solar radiation (MJ m$^{-2}$ yr$^{-1}$)</th>
<th>Relativity (%)</th>
<th>Wind speed (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>0.26*</td>
<td>-13.33*</td>
<td>-0.44</td>
<td>-0.16*</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>0.33*</td>
<td>-7.66*</td>
<td>-0.52*</td>
<td>-0.17*</td>
</tr>
<tr>
<td>Summer maize</td>
<td>0.19*</td>
<td>-5.67*</td>
<td>-0.36</td>
<td>-0.15*</td>
</tr>
<tr>
<td>Correlation coefficient</td>
<td>0.04</td>
<td>0.69*</td>
<td>0.57*</td>
<td>0.54*</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>-0.09</td>
<td>0.10</td>
<td>0.58*</td>
<td>0.35</td>
</tr>
<tr>
<td>Summer maize</td>
<td>0.16</td>
<td>0.66*</td>
<td>0.19</td>
<td>0.62*</td>
</tr>
</tbody>
</table>
wheat-summer maize rotation system can be applied to predict the agricultural water demand and will assist water resources planning and management for this region.

$ET_0$ during period of winter wheat accounted for the largest proportion of annual $ET_0$ due to its long phenological days, while as for summer maize growing season $ET_0$ decreased significantly with the magnitude of 0.5 mm yr$^{-1}$. Solar radiation is considered to be the most sensitive and primarily controlling variable for negative trend in $ET_0$ for summer maize growing season, and more sensitivity to solar radiation and temperature were detected in east part and southwest part of 3H plain respectively. While in winter wheat growing season relative humidity became the predominant factor, furthermore, declining relative humidity also primarily controlled a negative trend in $ET_0$. $ET_0$ in summer maize growing season was more sensitive to temperature fluctuation in east part of study area and $S_{RH}$ increased from northeast to southwest. For winter wheat growing season, $S_{RH}$ turned to increase from west to east and south. The eight sensitivity centrals (including $S_T$, $S_{RS}$, $S_{WS}$ and $S_{RH}$ of $ET_0$ in winter wheat and summer maize growing season, respectively) were all found located in Shandong Province. This fact is probably derived from the location of selected 40 meteorological sites and spatial pattern of sensitivity coefficients for these four key variables.

**MATERIALS AND METHODS**

**Study area and climate data**

The 3H plain, one of the largest plains in China, is located in the north of China and extends from 31°14′-40°25′N and 112°33′-120°17′E. The climate is temperate, sub-humid, and continental monsoon with a cumulative temperature (>0°C) of 4200 to 5500°C, average annual precipitation ranging from 500 to 800 mm (Ren et al. 2008). The annual rainfall concentrates in the summer period, from July to September. However, winter and spring is characterized by a lack of water for agricultural production. Although precipitation is insufficient for cultivation in this area, it is one of the main Chinese crop production centers, providing about 61 and 31% of wheat and maize production respectively (http://www.stats.gov.cn/), with intensive management characterized by the application of sufficient irrigation water and fertilizers. Accordingly, the main cropping system in the 3H plain is the winter wheat-summer maize rotation system (Zhao et al. 2006; Liang et al. 2011; Sun et al. 2011). Usually, winter wheat is sown at the beginning of October and harvested at June in the following year, summer maize is sown directly afterwards and harvested at the end of September.

Data set from 1961 to 2011 in 40 weather stations provided by China Meteorological Administration (CMA) were used in this study (Fig. 5). Daily observed maximum ($T_{max}$) and minimum air temperature ($T_{min}$), wind speed (WS) measured at 10 m height, average relative humidity (RH) and daily sunshine duration (SD) data were available. The weather stations were selected by the following two criteria. First, the spatial distribution had to guarantee such a coverage could be representative of irrigated lands in 3H plain. In addition, time series had to be long enough to obtain statistically significant results in trend analyses. Thus, the 51-yr period from 1961 to 2011 was studied when it was possible.

**Calculation of $ET_0$**

The Penman-Monteith formula recommended by the Food and Agriculture Organization of the United Nations (FAO) was used to calculate $ET_0$ over the past 51-yr. The Penman-Monteith formula is given as following:

$$ET_0 = \frac{0.408 \Delta (R_e - G) + \frac{900}{T + 273} U_e (e_s - e_a)}{\Delta + \gamma (1 + 0.34 U_e)} \quad (1)$$

In this formula, $ET_0$, crop reference evapotranspiration (mm d$^{-1}$); $\Delta$, saturation vapor pressure/temperature curve...
(kPa °C⁻¹); $R_n$, net radiation from canopy (MJ m⁻² d⁻¹); $G$, soil heat flux (MJ m⁻³ d⁻¹); $T$, the average daily temperature, equal to the mean of daily average maximum temperature ($T_{max}$) and average minimum temperature ($T_{min}$), °C; $U_w$, wind speed of 2 m height above the ground (m s⁻¹); $e_s$, saturation vapor pressure (kPa); $e_a$, actual water vapor pressure (kPa); $e_{sa}$, vapor pressure deficit (kPa); $\gamma$, psychrometer constant (kPa °C⁻¹). The related parameters of calculation methods in the formula were showed in the reference (Allen et al. 1998). All the above variables can be calculated from daily meteorological observation data. $R_n$ can be approached by the following formula:

$$R_n = R_{an} - R_{ao} \tag{2}$$

Where, $R_n$ is the net radiation (MJ m⁻² d⁻¹), $R_{an}$ is the difference between the incoming net shortwave radiation (MJ m⁻² d⁻¹), $R_{ao}$ is the outgoing longwave radiation (MJ m⁻² d⁻¹).

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

Where, $R_s$ is net solar or shortwave radiation (MJ m⁻² d⁻¹), $\alpha$ is albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop, $R_s$ is the incoming solar radiation (MJ m⁻² d⁻¹).

$$R_{ao} = \sigma \left[ \frac{T_{max}^4 + T_{min}^4}{2} \right] (0.34 + 1.35 \frac{R_s}{R_n} - 0.35) \tag{4}$$

Where, $R_{ao}$ is net outgoing longwave radiation (MJ m⁻² d⁻¹), $\sigma$ is Stefan-Boltzmann constant (4.903×10⁻⁸ MJ K⁻⁴ m⁻² d⁻¹), $T_{max}$ is minimum absolute temperature during the 24-h period, $T_{min}$ is maximum absolute temperature during the 24-h period, $e_a$ is actual vapour pressure [kPa], $R_s - R_{ao}$ is relative shortwave radiation, $R_s$ is solar radiation (MJ m⁻² d⁻¹), $R_{ao}$ clear-sky radiation (MJ m⁻² d⁻¹). The solar radiation ($R_s$) can be calculated with the Angstrom formula which relates solar radiation to extraterrestrial radiation and relative sunshine duration:

$$R_s = \left[ \frac{a + b \times \frac{n}{N} }{N} \right] \times R_s \tag{5}$$

Where, $R_s$ is solar or shortwave radiation (MJ m⁻² d⁻¹), $n$ is actual duration of sunshine (h), $N$ is maximum possible duration of sunshine or daylight hours (h), $R_s$ is extraterrestrial radiation (MJ m⁻² d⁻¹). The values of $a (=0.25)$ and $b (=0.5)$ are recommended by FAO.

Soil heat flux ($G$) is small compared to $R_n$ particularly when the surface is covered by vegetation and calculation time step is 24 h or longer. Thus, as the magnitude of the day or 10-d soil heat flux beneath the grass reference surface is relatively small, it can be ignored. That is $G_{an} \approx 0$.

For the calculation of $ET_0$, wind speed measured at 2 m above the surface is required. It can be converted from the normal measurement at 10 m wind speed based on the equation given by the FAO Penman-Monteith method (Allen et al. 1998) as following:

$$U_z = \frac{U_z \times 4.87}{\log(67.8 \times 10^{-5} - 5.42)} \tag{6}$$

Where $U_z$ is the wind speed at 2 m above ground surface (m s⁻¹), $U_z$ is the measured wind speed at Z m above ground surface (m s⁻¹), and $Z$ is the height of measurement above ground surface. Here $Z = 10$ m.

### Sensitivity analysis of $ET_0$ to meteorological variables

Sensitivity analysis was performed to evaluate the effect of meteorological variables on $ET_0$.

For a general definition of sensitivity, the variable $V$ is considered, which is a function of the input variables $x_1, x_2, x_n, \ldots, x_i$:

$$V = f(x_1, \ldots, x_i) \tag{7}$$

If the variables $x_1, x_2, x_n, \ldots, x_i$ are independent of $V$, it may be written:

$$V + \Delta V = f(x_1 + \Delta x_1, \ldots, x_i + \Delta x_i) \tag{8}$$

From a Taylor series expansion we have, neglecting higher-order terms:

$$\Delta V = \frac{\partial V}{\partial X_1} \Delta X_1 + \ldots + \frac{\partial V}{\partial X_n} \Delta X_n \tag{9}$$

By definition, the partial differentials, $\frac{\partial V}{\partial X_i}$, are the sensitivities, $S_{X_i}$, is the dependent variable $V$ to the independent input variable $X_i$ (McCuen 1974; Saxton 1975; Beven 1979; McCuen and Beighley 2003). They denote the change in $V$ per unit change in $X_i$.

From eq. (9) we have:

$$S_{X_i} = \frac{\partial V}{\partial X_i} \frac{\Delta V}{\Delta X_i} \tag{10}$$

Which shows that $S_{X_i}$ may be obtained by calculating directly the value of the partial differential, or by applying a step change in $X_i$ while leaving the variables other than $X_i$ constant. Here $S_{X_i}$ may be sensitive to the relative magnitude of $V$ and $X_i$. Therefore, $S_{X_i}$ may be divided by the ratio $\frac{V}{X_i}$, which leads to the relative sensitivity or sensitivity coefficient $R_{S_{X_i}}$:

$$R_{S_{X_i}} = \frac{\partial V}{\partial X_i} \frac{\Delta X_i}{\Delta V} \tag{11}$$

Now, the relative change in $V$ can be expressed as (Saxton 1975), which shows that the relative sensitivity coefficient denotes the part of the relative change in $X_i$ that is transferred to the relative change in $V$. If, for example, $R_{S_{X_i}}=25\%$, a 10% change in $X_i$ will result in a 2.5% change in $V$.

$$\frac{\Delta V}{V} = R_{S_{X_i}} \frac{\Delta X_i}{X_i} + \ldots + R_{S_{X_n}} \frac{\Delta X_n}{X_n} \tag{12}$$

### Sensitivity coefficients center analysis

In order to evaluate characteristic of sensitivity coefficients of meteorological parameters on $ET_0$, sensitivity coefficients centers were calculated based on gravity center analysis on the sensitivities of meteorological parameters. The gravity
center (Gaile 1984) is the point of equality of the regional force from all directions, which is usually denoted by certain attributes and geographic coordinates of the subunit (compared to the entire study area).

\[
\bar{X}_i = \frac{\sum (X_i E_i)}{E}, \quad \bar{Y}_i = \frac{\sum (Y_i E_i)}{E}
\]

\((13)\)

\(\bar{X}_i, \bar{Y}_i\) are the latitude and longitude of the sensitive center of meteorological parameter \(i\); \(X_y, Y_y\) are the latitude and longitude of grid \(j\) of \(i\). \(E_i\) is the sensitivity coefficients of \(i\) in grid \(j\). \(E\) is the accumulate sensitivity coefficients of \(i\) in all grids.

**Time series analysis method**

In order to understand the temporal variation of the climate variables, the linear trend and the associated periods were analyzed by a linear fitted model.

The least-square linear model is the most common method used for statistical diagnosis in modern climatic analysis studies (Zeng and Heilman 1997; Donohue et al. 2010; Liu et al. 2010), and it is a fundamental technology to forecast changes in modern climate. The linear trend was chosen because of being the simplest model for an unknown trend. The level of adequacy of the fitted model was measured by the percentage of variance explained by it. Linear trends for the series of annual total precipitation were estimated by the least square method and can be calculated by the least square regression. The estimated slopes were tested against the hypothesis of null slope by a 2-tailed \(T\)-test at a confidence level of 95% (Serrano et al. 1999).

A series \(y_1, y_2, \ldots, y_n\) can be expressed by the polynomial:

\[
y_i(t) = a_0 + a_1 t + \cdots + a_m t^n \quad (m<n)
\]

\((14)\)

Where, \(t\) is year. Generally, the linear trend of a time series can be estimated by the least square method and can be expressed by the linear regression equation as:

\[
y_i(t) = a_0 + a_1 t
\]

\((15)\)

Where, the slope \(a_1\) is the estimated trend.

**Acknowledgements**

This research was supported by the Key Technologies R&D Program of China during the 12th Five-Year Plan period (2012BAD09B01), the National 973 Program of China (2012CB955904), the Project of Food Security and Climate Change in the Asia-Pacific Region: Evaluating Mismatch between Crop Development and Water Availability and Project of National Non-profit Institute Fund, China-Australia (BSRF201206). We gratefully acknowledge the anonymous reviewers for their valuable comments on the manuscript.

**References**


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(Managing editor SUN Lu-juan)