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RESEARCH ARTICLE

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

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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.* 2009; Gonzalez Hidalgo *et al.* 2009; Espadafor *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 1 037.7 mm, with maximum value 1 155.5 mm, and minimum value

931.8 mm. Statistically significant decreasing trend at significance level of P<0.01were 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

	Average ET_0 (mm)	Maximum ET_0 (mm)	Minimum ET_0 (mm)	Slope (mm yr^{-1})	r
Annual	1037.7	1155.5	931.8	-1.3	0.39**
Winter wheat	682.2	765.8	591.5	-0.5	0.29
Summer maize	355.5	417.8	306.4	-0.8	0.54**

** 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 to 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.

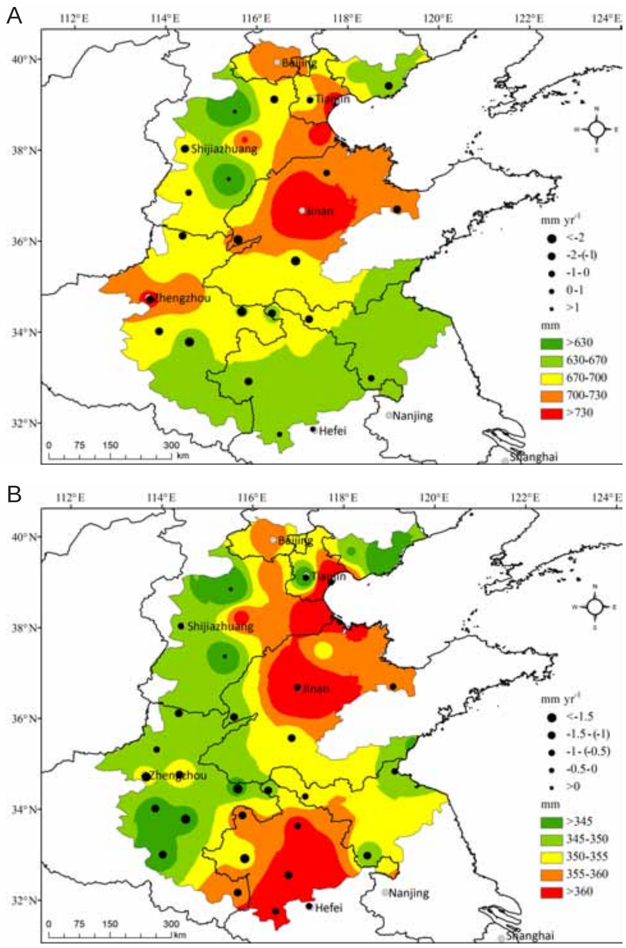

Fig. 1 Spatial pattern of ET_0 and its trend in winter wheat season and summer maize season in Huang-Huai-Hai plain (3H plain). A, winter wheat. B, summer maize.

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 Kriging 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 Henan and Jiangsu provinces. S_{WS} in winter wheat growing season showed opposite change pattern to S_{RS}, 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

	Mean	Maximum	Minimum	Slope (per decade)	r
S_T					
Annual	-0.267	-0.132	-0.331	-0.010	0.47**
Winter wheat	-0.159	0.009	-0.234	-0.014	0.42**
Summer maize	-0.592	-0.535	-0.679	-0.011	0.45**
S_{RS}					
Annual	0.428	0.469	0.376	-0.005	0.44**
Winter wheat	0.345	0.391	0.296	-0.004	0.33*
Summer maize	0.677	0.709	0.614	-0.089	0.44**
S_{WS}					
Annual	0.154	0.214	0.083	0.010	0.51**
Winter wheat	0.186	0.261	0.101	0.008	0.46**
Summer maize	0.058	0.101	0.027	0.007	0.55**
S_{RH}					
Annual	-1.189	-0.665	-2.121	0.080	0.42**
Winter wheat	-1.159	-0.634	-2.079	0.071	0.43**
Summer maize	-0.030	-0.020	-0.043	0.000	0.09

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

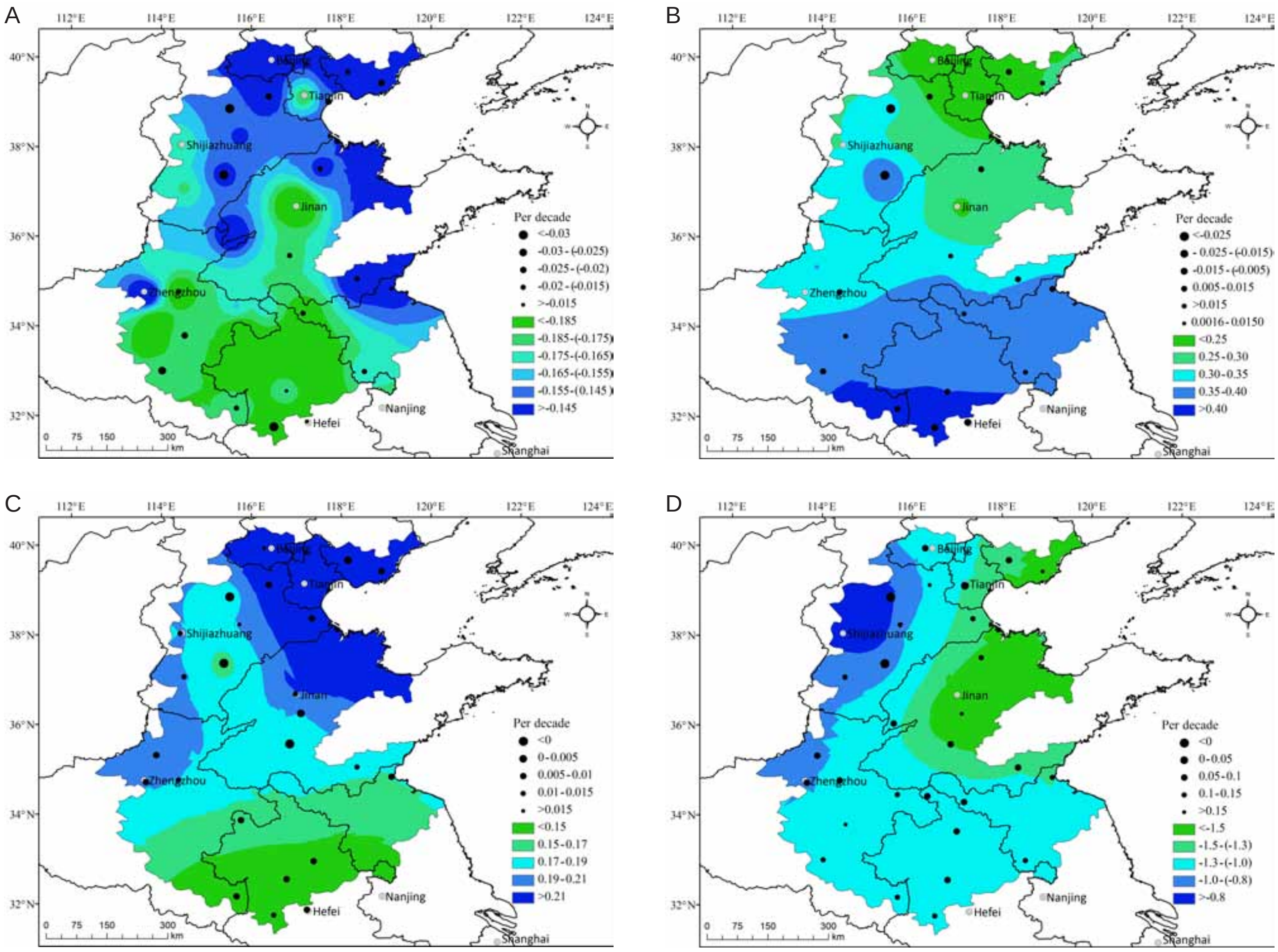

Fig. 2 Spatial variability in sensitivity coefficient of ET_0 in winter wheat season to temperature (S_T, A), solar radiation (S_{RS}, B), wind speed (S_{WS}, C) and relative humidity (S_{RH}, D).

S_{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,

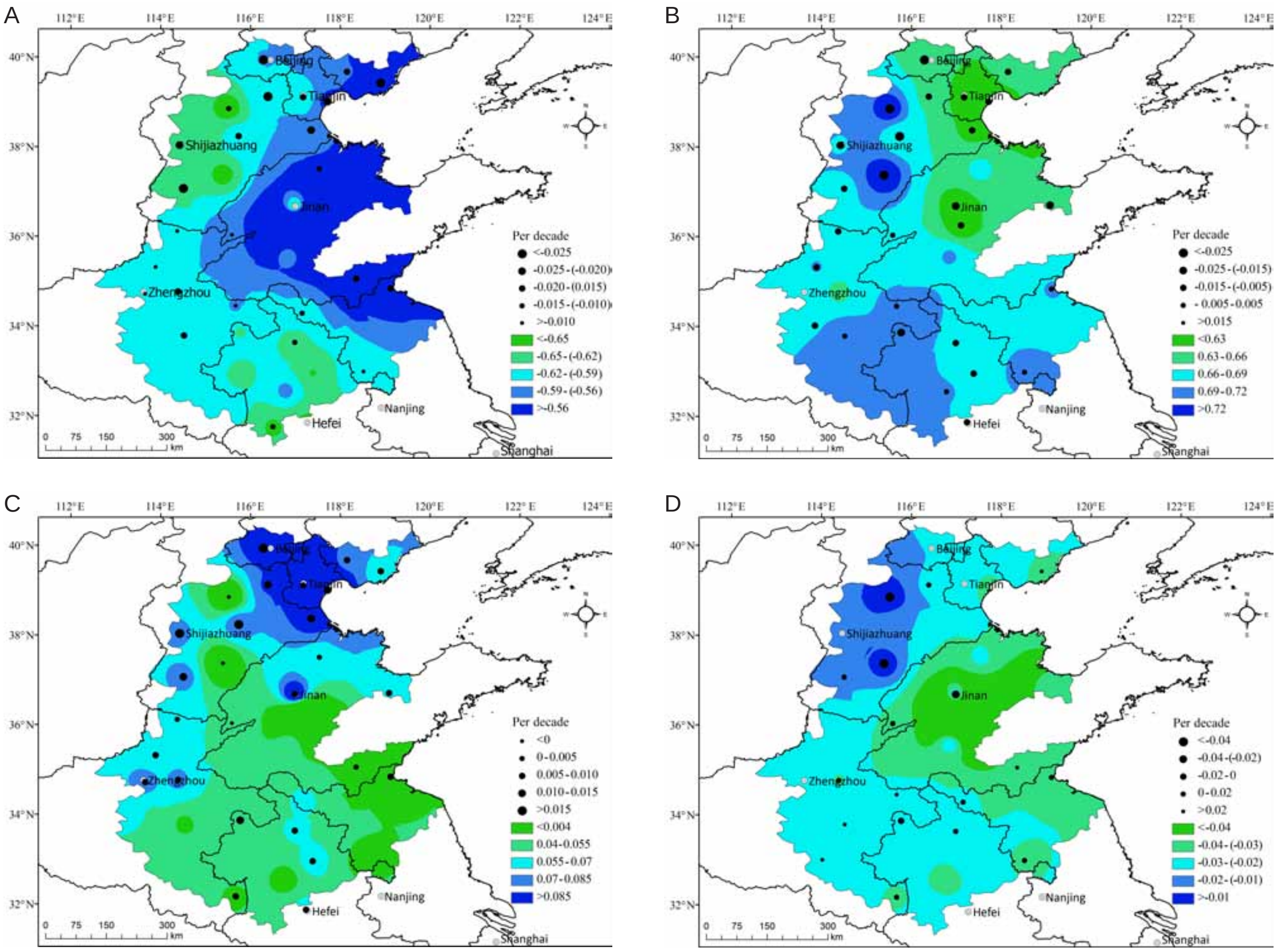

Fig. 3 Spatial variability in sensitivity coefficient of ET_0 in summer maize season to temperature (S_T, A), solar radiation (S_{RS}, B), wind speed (S_{WS}, C) and relative humidity (S_{RH}, D).

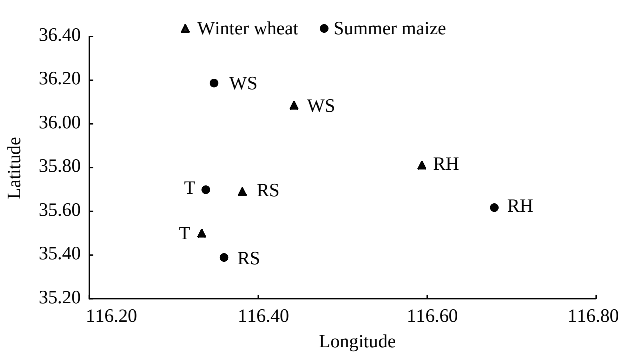

Fig. 4 Sensitivity central of ET_0 in winter wheat-summer maize growing season in 3H plain.

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

Table 3 The trend and correlation coefficients between annual ET_0 with key climatic variables in 3H plain

	Mean temperature (°C per decade)	Solar radiation (MJ m^{-2} yr^{-1})	Relativity humidity (%)	Wind speed (m s^{-1})
Trend				
Annual	0.26**	-13.33*	-0.44	-0.16**
Winter wheat	0.33**	-7.66**	-0.52*	-0.17**
Summer maize	0.19**	-5.67**	-0.36	-0.15**
Correlation coefficient				
Annual	0.04	0.69**	0.57**	0.54**
Winter wheat	-0.09	0.10	0.58**	0.35*
Summer maize	0.16	0.66**	0.19	0.62**

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, relativity 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 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 relativity humidity became the predominant factor, furthermore, declining relativity 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_{RS} increased from northeast to southwest. As 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 4 200 to 5 500°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.

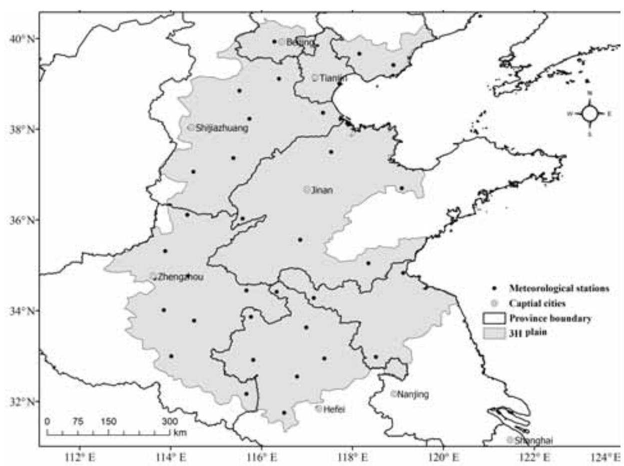

Fig. 5 The location of meteorological stations in 3H plain.

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:

$$ET_0=\frac{0.408\Delta(R_n\text{-}G)+\gamma\frac{900}{T+273}U_2(e_s\text{-}e_a)}{\Delta+\gamma(1+0.34U_2)} \tag{1}$$

In this formula, ET_0, crop reference evapotranspiration (mm d^{-1}); $\triangle$, 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^{-2} 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_2, 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_s-e_a, vapor pressure deficit (kPa); γ, 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:

$$R_n=R_{ns}-R_{nl} \quad (2)$$

Where, R_n is the net radiation (MJ m^{-2} d^{-1}), R_{ns} is the difference between the incoming net shortwave radiation (MJ m^{-2} d^{-1}), R_{nl} is the outgoing net longwave radiation (MJ m^{-2} d^{-1}).

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

Where, R_{ns} is net solar or shortwave radiation (MJ m^{-2} d^{-1}), α 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}).

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

Where, R_{nl} is net outgoing longwave radiation (MJ m^{-2} d^{-1}), σ is Stefan-Boltzmann constant (4.903×10^9 MJ K^{-4} m^{-2} d^{-1}), $T_{\max,k}$ is maximum absolute temperature during the 24-h period, $T_{\min,k}$ is minimum absolute temperature during the 24-h period, e_a is actual vapour pressure [kPa], R_s-R_{so} is relative shortwave radiation, R_s is solar radiation (MJ m^{-2} d^{-1}), R_{so} 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:

$$R_s=\left(a+b\times\frac{\mathrm{n}}{\mathrm{N}}\right)\times R_a \quad (5)$$

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_a 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 $G_{day}\approx 0$.

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:

$$U_2=\frac{U_Z\times 4.87}{\log_e(67.8\times 10-5.42)} \quad (6)$$

Where U_2 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 is 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_3, …, x_4:

$$V=f(x_1,...,x_n) \quad (7)$$

If the variables x_1, x_2, x_3,…, x_4 are independent of V, it may be written:

$$V+\Delta V=f(x_1+\Delta x_1,...,x_n+\Delta x_n) \quad (8)$$

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

$$\Delta V=\frac{\partial V}{\partial X_1}\Delta X_1+...+\frac{\partial V}{\partial X_n}\Delta X_n \quad (9)$$

By definition, the partial differentials, $\frac{\partial V}{\partial X_i}$, are the sensitivities, SX_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:

$$SX_i=\frac{\partial V}{\partial X_i}=\frac{\Delta V}{\Delta X_i} \quad (10)$$

Which shows that SX_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 SX_i may be sensitive to the relative magnitude of V and X_i. Therefore, SX_i may be divided by the ratio $\frac{V}{X_i}$, which leads to the relative sensitivity or sensitivity coefficient RSX_i:

$$RSX_i=\frac{\partial VX_i}{\partial X_i V} \quad (11)$$

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, RSX_i=25%, a 10% change in X_i will result in a 2.5% change in V.

$$\frac{\Delta V}{V}=RSX_1\frac{\Delta X_1}{X_1}+...+RSX_n\frac{\Delta X_n}{X_n} \quad (12)$$

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).

$$\overline{X_i} = \frac{\sum_{j=1}^{n}\left(X_{ij}E_{ij}\right)}{E}, \quad \overline{Y_i} = \frac{\sum_{j=1}^{n}\left(Y_{ij}E_{ij}\right)}{E} \tag{13}$$

$\overline{X_i}$, $\overline{Y_i}$ are the latitude and longitude of the sensitive center of meteorological parameter *i*; X_{ij}, Y_{ij} are the latitude and longitude of grid *j* of *i*. E_{ij} 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 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 calculated by the least square regression. The estimated slopes were tested against the hypothesis of null slope by means of a 2-tailed *T*-test at a confidence level of 95% (Serrano *et al.* 1999).

A series y_1, y_2, …y_i, …, y_n, can be expressed by the polynomial:

$$\hat{y}_n(t) = a_0 + a_1 t + \cdots + a_m t^n \quad (m<n) \tag{14}$$

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:

$$\hat{y}_n(t) = a_0 + a_1 t \tag{15}$$

Where, the slope a_1 is the estimated trend.

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