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4

Impacts of Climate Change on Crop Water Requirements in Huang-Huai-Hai Plain, China

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Abstract

Climate change will have important implications in the agriculture of water-short regions, such as Huang-Huai-Hai Plain (3H Plain), where expected warmer and drier conditions might augment crop water requirement (ET_c). To evaluate the effect of climate change, a data set consisting of observed daily values of air temperature, relative humidity, sunshine duration and wind speed from five selected weather stations in the 3H Plain and covering the period 1981–2009 was used for estimating reference evapotranspiration (ET_0). ET_0 was calculated using FAO-56 Penman–Monteith equation; then sensitivity coefficient of $\mathrm{ET_c}$ of major climatic variables and regional responses of precipitation deficit to climate change were conducted in the 3H Plain. The results showed that a clear drop in solar radiation (SR) was detected and temperatures increased, especially the minimum temperature. Wind speed (WS) decreased significantly in most of the stations, especially from seeding to jointing stages for wheat. No significant change was detected for relative humidity (RH) in 1981–2009. Temperature was the most sensitive variable in general for the plain, followed by SR, WS and RH. The decrease of sensitivity coefficient of solar radiation (S_{SR}) mainly occurred in seeding to jointing stages and heading to maturity stages of winter wheat. Sensitivity coefficient of temperatures (S_{T}) increased in Beijing, Xinxiang, Xuzhou and Yanzhou stations, which means that an increase in temperatures may lead to a larger increase of ET_c in these four stations. However, S_{T} decreased in the Shijiazhuang station. With the decrease of WS, ET_c will decrease due to the positive coefficient in Beijing and Xinxiang stations. Trends of S_{RH} showed no significant changes in the time series analysis. A positive relationship was detected between precipitation deficit and relative humidity, and the latter was considered the most correlative factor for precipitation deficit.

4.1 Introduction

Climate change with the characteristic of global warming has become a hotspot of research in the field of water resources, agriculture, ecology and other disciplines. According to the IPCC report, in the recent 100 year period (1906–2005) the global temperature has risen by 0.74°C (IPCC, 2007). Climate model projections summarized in the 2007 IPCC report indicate that the global surface temperature is likely to rise further by 1.1–6.4°C during the 21st century.

Agriculture is directly affected by climatic conditions and changes. Changes in

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climatic elements such as temperature, precipitation, radiation, humidity and WS could have profound implications on hydrologic processes in agriculture (McKenney and Rosenberg, 1993). Therefore it is essential to understand the impact of climate change on agricultural water resources for sustainable agriculture and to study methods to minimize the negative effects caused by such changes. It is also necessary to evaluate effects of climate changes in terms of temperature rise, amounts of SR, WS and RH changes. Xiong *et al.* (2010) reported that there would be insufficient water for agriculture in China in the coming decades, due primarily to increases in water demand for non-agricultural uses, which would have significant implications for adaptation strategies and policies for agricultural production and water management.

Crop water requirement is decided from reference evapotranspiration (ET_0) estimation methods suggested, usually, by Food and Agriculture Organization of the United Nations (FAO). In 1977, FAO presented guidelines for predicting crop water requirements. The guidelines suggested methods to derive crop water requirements and discussed the application of data on crop water requirements in irrigation project planning, design and operation. ET_0 refers to the crop evapotranspiration in the open short grassland where the soil moisture is adequate, the ground is completely covered, and grass grows normally at a 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 and is essentially dependent on four meteorological variables: air temperature, SR, RH and WS (Allen *et al.*, 1998). One or more of these four meteorological variables can be taken into account, depending on the ET_0 calculation method selected. The main advantage of the Penman–Monteith approach is that it takes into account the most significant variables, so that the influence of each of them to ET_c can also be analysed (Blaney and Criddle, 1952; Hargreaves and Samani, 1982) on physically based equations requiring daily data for temperature and RH of the air, SR and WS (Allen *et al.*, 1998). Several studies have carried out sensitivity analyses of ET_0 to determine meteorological data in different climates (Rana and Katerji, 1998; Goyal, 2004; Irmak *et al.*, 2006), but they were restricted to a single station. Furthermore, what has been reported to be the most effective variable detected is WS (Todisco and Vergni, 2008), SR (Gao *et al.*, 2006; Wang *et al.*, 2007) and RH (Gong *et al.*, 2006) in other papers; however, these studies were almost restricted to monthly, seasonal or annual ET_0. Liu, Y. *et al.* (2010) reported that annual ET_0 and its constituents (ET_{rad} and ET_{aero}) had significantly declined, while the spring ET_{aero} value was the highest across the North China Plain (NCP). Song *et al.* (2009) 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 WS had a bigger impact on ET_0 rates than the increases observed by the maximum and minimum temperatures. However, studies about sensitivity analyses of ET_0 then ET_c during the typical crop growing season and its trend in variation are rarely seen in the 3H Plain.

The objectives of this chapter are: (i) to investigate the trends for ET_c for winter wheat in the 3H Plain in the past; (ii) to evaluate the major factors related to the changes in ET_c; and (iii) to compare the temporal variations of climatology sensitivity coefficients in different stations, in an attempt to understand the relative roles of the main climatic variables.

4.2 Materials and Methods

4.2.1 Study area and climate data

The 3H Plain, one of the largest plains in China, is located in the north of the country and extends from 31°14′ to 40°25′ N and from 112°33′ to 120°17′ E, stretching over an area of about 350,000 km^2. The plain is

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mainly formed by the alluvial deposits of the Yellow, Huai and Hai rivers. Almost the entire plain is found at an altitude below 50 m above sea level and the slope gradient is less than 3°. The climate is temperate, subhumid, and continental monsoon with a cumulative temperature (>0°C) of 4200–5500°C, a frost-free period of about 170–220 days and average annual precipitation ranging between 500 and 800 mm (Ren *et al*., 2008). The annual rainfall concentrates in the summer period, from July to September. On the other hand, it is characterized by a lack of water for agricultural production in winter. Although precipitation is insufficient for cultivation in the 3H Plain, it is the largest agricultural production area in China, accounting for around 50% of the wheat (Wang *et al*., 2009). Li *et al*. (2010) reported that the 3H Plain provided 42.3% of the total national winter wheat and summer maize production with intensive management characterized by the application of sufficient irrigation water and fertilizers.

Data from five weather stations provided by China Meteorological Administration (CMA) were used in this chapter (Fig. 4.1). Daily data observed from 1981 to 2009 on maximum temperature (T_{max}) and minimum air temperature (T_{min}), precipitation (P), wind speed (WS) measured at 10 m height, with average relative humidity (RH) and daily sunshine duration (representing SR) were available. The weather stations were selected by the two following criteria: (i) the spatial distribution had to guarantee such a coverage that could be representative of irrigated lands in the 3H Plain; and (ii) the time series had to be long enough to obtain statistically significant results in trend analyses.

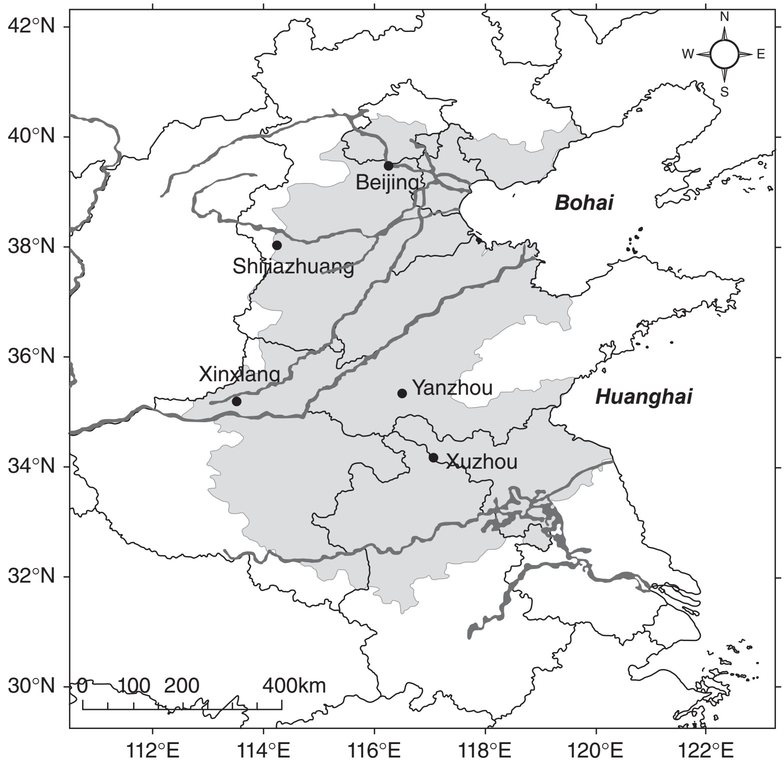

Fig. 4.1. Location of the weather stations selected in this chapter.

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Table 4.1. Annual variation tendency and statistics of the five phenological phases for winter wheat at the five selected stations.

Name of station	Phenological phase	Maximum value	Average value	Minimum value	Slope[a]
Beijing	Sowing date	287	275	262	0.57**
	Seeding date	297	268	285	0.64**
	Jointing date	126	104	112	–0.33**
	Heading date	140	123	131	–0.24**
	Maturity date	174	159	168	–0.20**
Shijiazhuang	Sowing date	288	278	271	0.09
	Seeding date	300	286	277	0.17
	Jointing date	108	99	87	–0.24**
	Heading date	129	120	112	–0.26**
	Maturity date	164	160	156	0.05
Yanzhou	Sowing date	299	281	272	0.12
	Seeding date	308	288	280	0.14
	Jointing date	100	90	78	–0.42**
	Heading date	124	114	101	–0.31**
	Maturity date	165	156	150	–0.08
Xinxiang	Sowing date	293	284	276	0.04
	Seeding date	303	292	283	0.10
	Jointing date	102	87	75	–0.55**
	Heading date	123	113	102	–0.33**
	Maturity date	158	152	147	–0.12
Xuzhou	Sowing date	297	285	276	0.17
	Seeding date	308	293	281	0.19
	Jointing date	99	82	66	–0.64**
	Heading date	121	113	102	–0.34**
	Maturity date	162	155	149	–0.21**

[a] Linear coefficients significant at $*p < 0.05$, $**p < 0.01$ and $***p < 0.001$.

4.2.2 Phenological data

Data on the date of sowing, seeding, jointing, heading and maturity of winter wheat (representing Julian Day) were provided by CMA for the period 1981–2009. As described in Table 4.1, information on the latest period for sowing, seeding, jointing, heading and maturity dates of winter wheat are found in Yanzhou and Beijing stations, respectively. Similarly, information on the earliest period for these five dates is found in Beijing, Shijiazhuang, Xuzhou, Yanzhou and Xinxiang stations. Sowing and seeding dates in the five stations are observed to be delayed with the biggest amplitude of 0.57 and 0.64 days year^{-1} in the Beijing Station. However, jointing, heading and maturity dates are nearly observed to advance with the biggest amplitude of 0.64, 0.34 and 0.21 days year^{-1} in the Xuzhou Station.

4.2.3 Crop coefficient approach

Crop coefficients (K_c) vary for different crops and the growing stage of the crop. In this chapter, coefficient of winter wheat was developed by FAO (Table 4.2), and the coefficient of daily winter wheat can be obtained in relation to climatic conditions for phenological phases for winter wheat (Allen *et al.*, 1998).

Table 4.2. Crop coefficients of winter wheat in different phases.

Phenological phase	K_c
K_{cini}	0.70
K_{cmid}	1.15
K_{cend}	0.40

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4.2.4 Calculation of precipitation deficit by the FAO Penman–Monteith method

In this chapter, the precipitation deficit is defined as the difference between effective precipitation and the crop water requirement in the duration of the whole crop and during the four different stages *i* of winter wheat.

$$PD = P_{\mathrm{e}} - ET_{\mathrm{c}} \tag{4.1}$$

where PD is the precipitation deficit (mm), P_{e} is the effective precipitation (mm) and ET_{c} is the crop water requirement (mm).

Effective precipitation is defined as the total precipitation minus deep percolation, runoff and evaporation. The method of effective precipitation analysed in this chapter is from the US Department of Agriculture Soil Conservation Service. It is one of the most popular methods to calculate effective precipitation and has proven to be effective in many research studies (Smith, 1992; Döll, 2002).

$$\begin{aligned} &P_{\mathrm{e}} = P \times \left(4.17 - 0.2 \times P\right) / 4.17 \\ &\quad P < 8.3\,\mathrm{mm\ day}^{-1} \\ &P_{\mathrm{e}} = 4.17 + 0.1 \times P \quad P \geq 8.3\,\mathrm{mm\ day}^{-1} \end{aligned} \tag{4.2}$$

where P is precipitation detected in weather station.

ET_0 is the evapotranspiration from disease-free, well-fertilized crops grown in large fields under optimum soil water conditions and achieving full production under the given climatic conditions. The crop water requirement can be calculated from climatic data and by directly combining the crop resistance, albedo and air resistance factors under standard conditions (Allen *et al.*, 1998).

$$ET_{\mathrm{c}} = k_{\mathrm{c}} \times ET_0 \tag{4.3}$$

where ET_{c} is the crop water requirement (mm), k_{c} is the crop coefficient and ET_0 is the reference crop evapotranspiration (mm).

The FAO Penman–Monteith method to estimate ET_0 can be derived from the original Penman–Monteith equation and the equations of the aerodynamic and surface resistance (Allen *et al.*, 1998).

$$ET_0 = \frac{0.408\Delta\left(R_{\mathrm{n}} - G\right) + \gamma \frac{900}{T + 273} U_2 \left(e_{\mathrm{s}} - e_{\mathrm{a}}\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} \tag{4.4}$$

where, ET_0 is reference evapotranspiration (mm day^{-1}), Δ is the slope of the saturation vapour pressure curve (kPa °C^{-1}), R_{n} is the net radiation at the surface (MJ m^{-2} day^{-1}), G is the soil heat flux (MJ m^{-2} day^{-1}), $R_{\mathrm{n}} - G$ is the available energy (MJ m^{-2} day^{-1}), γ the psychrometric constant (kPa °C^{-1}), T is the mean temperature at 2 m height (°C), U_2 is the mean daily wind speed at 2 m height (m s^{-1}), e_{s} is the saturation vapour pressure (kPa), e_{a} is the actual vapour pressure (kPa) and $e_{\mathrm{s}} - e_{\mathrm{a}}$ is the vapour pressure deficit (kPa). The computation of all data required for calculating daily reference evapotranspiration followed the procedures in the FAO irrigation paper 56 (Allen *et al.*, 1998). To obtain the total monthly evapotranspiration, Eqn 4.4 was multiplied by the number of days in a given month.

All the above variables can be calculated from daily meteorological observation data. For the calculation of ET_0, wind speed measured at 2 m above the ground surface is required. It can be converted from the normal measurement at 10 m WS based on the equation given by the FAO Penman–Monteith method (Allen *et al.*, 1998) as follows:

$$U_2 = \frac{U_z \times 4.87}{\log_e\left(67.8 \times 10 - 5.42\right)} \tag{4.5}$$

where, U_2 is the wind speed at 2 m above ground surface (m s^{-1}), U_z is the measured wind speed at 10 m above ground surface (m s^{-1}).

4.2.5 Sensitivity analysis of crop water requirement to meteorological variables

In order to evaluate the effect of meteorological parameters on ET_{c}, a sensitivity analysis is performed to find more sensitive parameters.

For a general definition of sensitivity, the variable V is considered, which is a function of the input variables $x_1, x_2, x_3 \ldots x_n$:

$$V = f\left(x_1, \ldots, x_n\right) \tag{4.6}$$

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If the variables $x_1, x_2, x_3 \ldots x_n$ are independent of V, it may be written:

$$V + \Delta V = f\left(x_1 + \Delta x_1, \ldots, x_n + \Delta x_n\right) \tag{4.7}$$

Neglecting higher-order terms, from a Taylor series expansion we have:

$$\Delta V + \frac{\partial V}{\partial X_1}\Delta X_1 + \ldots + \frac{\partial V}{\partial X_n}\Delta X_n \tag{4.8}$$

By definition, the partial differentials, $\frac{\partial V}{\partial X_i}$, are the sensitivities and SX_i is the dependent variable V of 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 Eqn 4.8 we have:

$$SX_i = \frac{\partial V}{\partial X_i} = \frac{\Delta V}{\Delta X_i} \tag{4.9}$$

which shows that SX_i may be obtained by directly calculating 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 V/X_i, which leads to the relative sensitivity or sensitivity coefficient RSX_i:

$$RSX_i = \frac{\partial V X_i}{\partial X_i V} \tag{4.10}$$

Now, the relative change in V can be expressed as Eqn (4.11) (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.

$$\frac{\Delta V}{V} = RSX_1 \frac{\Delta X_1}{X_1} + \ldots + RSX_n \frac{\Delta X_n}{X_n} \tag{4.11}$$

4.2.6 Time series analysis method

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

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

A series $y_1, y_2 \ldots y_i \ldots y_n$, can be expressed by the polynomial:

$$\hat{y}_n(t) = a_0 + a_1 t + \ldots + a_m t^n \tag{4.12}$$

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:

$$\hat{y}_n(t) = a_0 + a_1 t \tag{4.13}$$

where, the slope a_1 is the estimated trend.

4.3 Results

4.3.1 Trends and persistence of crop water requirement in different phenological phases

In order to appreciate the temporal variability of ET_c changes and their magnitudes, ET_c series of phenological phases at each station were tested. As described in Table 4.3, the mean value of ET_c in the whole growth stage is from 391.9 to 462.2 mm, with the minimum value detected in the Yanzhou station and maximum value in the Beijing station. The ET_c in the four stations showed a negative trend, with ET_c decreasing significantly only in the Yanzhou station. However, there is also a significant increasing trend found in the analysis, such as ET_c in the Xinxiang station, in which station was detected a significantly increasing trend in the whole growth stage of winter wheat, with a slope of 1.57 mm year^{-1}.

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ET_c in seeding to jointing stages was detected with a significantly decreasing trend in the stations selected, and the minimum value, that is 1.81 mm for the slope, was found in the Beijing station. However, in the heading to maturity stages of winter wheat, the ET_c increased in the time series. The maximum value for slope, which is 1.61 mm, was detected in the Xinxiang station. In the jointing to heading stages of winter wheat, no significant trend was detected in this time series.

4.3.2 Inter-annual variation of relative moisture index

Relative moisture index is one of the common drought indexes, such as Z (Ju *et al.*, 1998), BMDI (Bhalme and Mooley, 1980) and PDSI (Szinell *et al.*, 1998), to evaluate dry condition in the 3H Plain (Li *et al.*, 2012). It can be concluded that there were varying degrees of drought in sowing to seeding, seeding to jointing, jointing to heading, heading to maturity and sowing to maturity for winter wheat from the characteristics and trends of relative moisture index of the 3H Plain (Table 4.4). According to the average value of five stations, each relative moisture index was less than –0.4, which means that sowing to seeding and heading to maturity are in light drought condition, and that sowing to maturity, seeding to jointing, and jointing to heading are in moderate drought condition. As for each station, a wet condition is detected in sowing to seeding stages in Xinxiang, Xuzhou and Yanzhou stations, and a serious drought condition is detected during seeding to jointing stages in Beijing and during jointing to heading stages in the Shijiazhuang station. As described, a wet trend was observed during jointing to heading

Table 4.3. Long-term trends over the entire studied period of crop water requirement (ET_c, mm) in different phenological phases for the selected weather stations.

	Sowing to maturity		Sowing to seeding		Seeding to jointing		Jointing to heading		Heading to maturity	
Station	Mean	Slope	Mean	Slope	Mean	Slope	Mean	Slope	Mean	Slope
Beijing	462.24	–0.67	8.42	–0.04	278.29	–1.81**	79.78	0.50	95.74	0.69*
Shijiazhuang	404.69	–0.44	6.01	0.05	194.68	–1.04*	89.07	–0.42	114.92	0.96*
Xinxiang	391.93	1.57**	6.09	0.09**	166.09	–0.26**	92.17	0.13	127.58	1.61**
Xuzhou	391.99	–0.59	6.85	0.01	152.13	–1.59**	99.56	0.05	133.44	0.93*
Yanzhou	396.00	–1.11*	6.10	–0.01	171.12	–1.31**	86.43	–0.35	132.34	0.57

* and ** represent linear coefficients significant at $p < 0.05$ and $p < 0.01$, respectively.

Table 4.4. The characteristics and trends of relative moisture index (M) in the selected weather stations.

	Sowing to maturity		Sowing to seeding		Seeding to jointing		Jointing to heading		Heading to maturity	
Station	Mean	Slope (/10 yr)	Mean	Slope (/10 yr)	Mean	Slope (/10 yr)	Mean	Slope (/10 yr)	Mean	Slope (/10 yr)
Beijing	–0.797	0.014	–0.766	0.000	–0.854	0.000	–0.743	0.071	–0.713	0.01
Shijiazhuang	–0.746	0.012	–0.610	0.185	–0.774	–0.003	–0.807	0.033	–0.674	0.000
Xinxiang	–0.697	–0.037	–0.311	–0.329	–0.738	–0.018	–0.791	0.085*	–0.598	–0.111
Xuzhou	–0.498	–0.011	–0.137	–0.833*	–0.436	0.050	–0.653	0.023	–0.467	–0.040
Yanzhou	–0.644	0.025	–0.264	0.208	–0.664	–0.003	–0.712	0.181**	–0.599	–0.025

* and ** represent linear coefficients significant at $p < 0.05$ and $p < 0.01$, respectively.
Slope is calculated for each 10-year period.

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stages in Xinxiang and Yanzhou stations. However, the relative moisture index of winter decreased significantly from sowing to seeding stages in Xuzhou.

4.3.3 Trends and persistence of meteorological variables

Investigation of trends and persistence in historical meteorological dates is helpful in understanding the effect of climate change on crop water requirement in the stations. An analysis of the average climate factors was carried out in different phenological phases for winter wheat (Table 4.5). As described in Table 4.5, the highest P_e is found in Xuzhou station, followed by Yanzhou, Xinxiang, Shijiazhuang and Beijing stations, but no significantly increasing or decreasing trend is detected for every phenological phase in these five stations. Likewise, the highest SR is found in the Beijing station, followed by Yanzhou, Shijiazhuang, Xuzhou and Xinxiang stations, and a decreasing trend was detected in annual SR for the analysed locations in sowing to maturity stages. Furthermore, the average trend was $-145.04\,\mathrm{MJ\,m^{-2}}$ 10 $\mathrm{year^{-1}}$ with a value range of between $-87.64\,\mathrm{MJ\,m^{-2}}$ 10 $\mathrm{year^{-1}}$ for the Shijiazhuang station and $-225.36\,\mathrm{MJ\,m^{-2}}$ 10 $\mathrm{year^{-1}}$ for the Beijing station. The decreased reduction in SR was higher and statistically significant in the regional scale from seeding to jointing stages compared with other stages. However, no significant change was detected in RH except in the Xinxiang station and a significantly decreasing trend was found ($p < 0.01$) for RH in the whole growth stage of winter wheat, and a slope of –1.56. T_{min} in the four stations (except Beijing station) was found to have a significant trend such that it increases. The increase in T_{min} was higher and more statistically significant from seeding to jointing stages, with 0.57°C 10 $\mathrm{year^{-1}}$. Compared to T_{min}, only the Yanzhou station has been detected to have a significantly increasing trend in T_{max}. Generally, the presence of increasing tendencies is higher in T_{min} than in T_{max}. WS in the Shijiazhuang and Xuzhou stations decreased significantly ($p < 0.01$), while it increased significantly in the Xinxiang station. No significant changes were detected in the Beijing and Yanzhou stations for WS.

4.3.4 Sensitivity coefficients of crop water requirement for climatic variables

A large number of research studies showed that a negative correlation exists between RH and ET_0 (Zeng and Heilman, 1997; Gong *et al.*, 2006) and a positive correlation exists between WS, SR, temperature and ET_c. The most effective meteorological factor that impacts ET_c is diverse in different stations and phenological stages for winter wheat. It cannot be denied that sensitivity coefficients exhibit large fluctuations during the growth stage of winter wheat. The primary meteorological factor and its influence on ET_c in the five stations were determined by a sensitivity correlation analysis. ET_c has a significant correlation with T_{min}, T_{max}, RH, WS and SR. According to the long-term trends analysis over the entire studied period of meteorological variables and sensitivities in the selected weather stations, RH has a negative correlation with ET_c, namely, that a decrease of RH has led to an increase of ET_c. SR, T_{min} and T_{max}, and WS showed a positive correlation with ET_c, that is, a decrease of WS, T_{min} and T_{max} has led to a decrease of ET_c. Temperature was the most sensitive variable to the ET_c in the whole growth stage of winter wheat, followed by SR, WS and RH. However, ET_c was observed to be more sensitive to T_{max} than to T_{min}. ET_c is more sensitive to temperatures in the sowing to seeding stages. As for SR, ET_c is more sensitive from sowing to seeding stages, jointing to heading stages and heading to maturity stages. ET_c in seeding to jointing stages was more sensitive to WS than in other phenological phases. A negative correlation exists between RH and ET_c, especially from seeding to jointing stages.

Table 4.6 shows the results of sensitive changes in ET_c in five stations selected in the 3H Plain. Trends of sensitivity coefficient of

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Table 4.5. Long-term trends over the entire studied period of the main meteorological variables in the selected weather stations.

	Sowing to maturity		Sowing to seeding		Seeding to jointing		Jointing to heading		Heading to maturity	
Station	Mean	Slope	Mean	Slope	Mean	Slope	Mean	Slope	Mean	Slope
P_e (mm 10 year^{-1})										
Beijing	67.09	0.55	3.09	–0.40	31.48	–2.19	9.27	1.84	23.25	1.29
Shijiazhuang	70.52	0.58	2.41	0.20	35.46	–3.26	7.78	0.55	24.88	3.09
Xinxiang	74.80	–4.40	5.43	–2.08	36.81	–3.08	9.13	2.72	23.43	–1.96
Xuzhou	117.80	–4.11	4.75	–2.62	64.24	–1.31	15.99	0.76	32.83	–0.94
Yanzhou	86.63	0.36	3.81	0.78	45.61	–3.40	9.50	1.86	27.71	1.12
SR (MJ m^{-2} 10 year^{-1})										
Beijing	3572.5	–225.4**	134.9	–7.4	2222.1	–201.5**	402.4	0.2	813.2	–16.6
Shijiazhuang	3239.8	–87.6*	101.1	3.6	1890.1	–122.9**	402.5	–21.7	846.2	53.5**
Xinxiang	2992.4	–95.7**	99.9	4.9	1645.9	–139.9**	457.1	13.3	789.4	25.9
Xuzhou	3117.6	–123.9**	116.5	4.0	1615.9	–157.3**	538.1	28.3	847.1	1.0
Yanzhou	3282.6	–192.5**	102.3	–7.1	1834.3	–179.1**	447.2	–9.4	898.9	3.1
RH (per cent 10 year^{-1})										
Beijing	48.51	–0.33	61.88	0.23	47.31	–0.17	45.86	–0.45	52.78	–2.06
Shijiazhuang	56.33	–1.99	65.63	–0.78	56.54	–2.17	50.84	–0.47	56.51	–2.70
Xinxiang	63.48	–1.56*	71.86	–1.82	63.55	–1.36	59.04	–2.39	64.33	–1.64
Xuzhou	65.43	0.79	69.23	–1.30	66.65	1.42	60.41	–0.61	63.93	0.43
Yanzhou	66.20	1.01	72.30	1.22	66.66	1.07	60.14	1.25	66.69	0.98
T_{min} (°C 10 year^{-1})										
Beijing	2.99	0.19	11.68	–0.18	–0.79	0.11	11.46	–0.65*	16.21	–0.44*
Shijiazhuang	3.89	1.01**	12.31	1.08*	0.22	1.02**	9.83	–0.16	15.56	0.20
Xinxiang	3.99	0.68**	11.63	0.83	0.49	0.65**	8.29	–0.35	14.27	–0.13
Xuzhou	4.92	0.55**	12.36	0.61	1.35	0.61**	7.66	–0.56	14.76	–0.30
Yanzhou	2.91	0.41**	11.30	0.97	–0.55	0.46**	6.69	–0.59*	13.08	–0.48**
T_{max} (°C 10 year^{-1})										
Beijing	13.66	–0.13	22.78	–1.35*	9.52	–0.25	23.37	–0.87**	28.02	–0.51
Shijiazhuang	14.45	0.19	23.83	–0.88	10.33	0.17	21.68	–0.82**	27.28	–0.53*
Xinxiang	14.64	0.21	22.33	0.56	10.83	0.22	19.88	–1.09*	25.67	–0.72**
Xuzhou	14.70	0.19	23.33	0.61	10.67	0.24	18.29	–0.90	25.50	–0.88**
Yanzhou	14.57	0.29**	23.78	0.18	10.72	0.38*	19.58	–0.80*	25.56	–0.69**
WS (m s^{-1} 10 year^{-1})										
Beijing	2.48	–0.03	2.01	0.00	2.44	–0.05	2.94	–0.08	2.59	0.08
Shijiazhuang	1.75	–0.23**	1.38	–0.17*	1.65	–0.24**	2.24	–0.34**	2.00	–0.19**
Xinxiang	2.15	0.19**	1.66	0.10	2.02	0.17**	2.64	0.19*	2.41	0.28**
Xuzhou	2.24	–0.17**	1.71	–0.25*	2.06	–0.19**	2.66	–0.13*	2.67	–0.19**
Yanzhou	2.48	–0.15	1.76	–0.06	2.36	–0.13	2.96	–0.20	2.81	–0.22*

P_e, effective precipitation; SR, solar radiation; T_{max}, maximum temperature; T_{min}, minimum temperature; RH, relative humidity; WS, wind speed.
* and ** represent linear coefficients significant at $p < 0.05$ and $p < 0.01$, respectively.

solar radiation (S_{SR}) are negative in Beijing and Xinxiang stations in the whole growth stage of winter wheat, with a $p < 0.01$ level of significance. The decrease of S_{SR} mainly occurred from seeding to jointing stages and heading to maturity stages of winter wheat, which means that the fluctuation of SR controlled less the changes of ET_c from seeding to jointing stages and from heading to maturity stages of winter wheat in Beijing and

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Table 4.6. Long-term trends over the entire studied stage of meteorological variables and sensitivities in the selected weather stations.

	Sowing to maturity		Sowing to seeding		Seeding to jointing		Jointing to heading		Heading to maturity	
Station	Mean	Slope	Mean	Slope	Mean	Slope	Mean	Slope	Mean	Slope
S_{SR}										
Beijing	0.19	–0.02**	0.41	–0.05**	0.09	–0.02**	0.42	–0.02	0.52	–0.03**
Shijiazhuang	0.26	–0.01	0.47	–0.01	0.15	–0.02**	0.46	0.00	0.57	–0.01
Xinxiang	0.31	–0.03**	0.48	–0.02	0.21	–0.03**	0.46	–0.05**	0.58	–0.04**
Xuzhou	0.33	0.00	0.50	0.01	0.24	0.00	0.46	–0.02**	0.56	0.00
Yanzhou	0.31	0.00	0.51	–0.01	0.22	–0.01	0.46	–0.01	0.57	0.00
S_{RH}										
Beijing	–0.01	0.00	0.00	0.00	–0.01	0.00	0.00	0.00	0.00	0.00
Shijiazhuang	–0.01	0.00	0.00	0.00	–0.01	0.00	0.00	0.00	0.00	0.00
Xinxiang	–0.01	0.00	0.00	0.00	–0.01	0.00	0.00	0.00	0.00	0.00
Xuzhou	–0.01	0.00	0.00	0.00	–0.01	0.00	0.00	0.00	0.00	0.00
Yanzhou	–0.01	0.00	0.00	0.00	–0.02	0.00	0.00	0.00	0.00	0.00
S_{Tmin}										
Beijing	0.34	0.02	0.53	0.07**	0.30	0.01	0.42	0.01	0.45	0.02*
Shijiazhuang	0.35	–0.02**	0.44	0.01	0.33	–0.03*	0.38	–0.02**	0.39	–0.02**
Xinxiang	0.45	0.04**	0.56	0.04	0.43	0.04**	0.45	0.03	0.47	0.05**
Xuzhou	0.53	0.01	0.55	–0.08	0.53	0.02	0.50	–0.01	0.54	–0.01
Yanzhou	0.53	0.02	0.54	0.04	0.54	0.03	0.47	0.00	0.52	0.00
S_{Tmax}										
Beijing	0.75	0.02	1.10	0.06	0.67	0.01	0.92	0.01	0.94	0.03
Shijiazhuang	0.76	–0.08**	0.95	–0.10**	0.73	–0.09**	0.84	–0.08**	0.83	–0.07**
Xinxiang	0.94	0.05*	1.11	0.06	0.93	0.05*	0.97	0.03	0.97	0.07**
Xuzhou	1.04	0.00	1.08	–0.14	1.04	0.02	1.02	–0.03	1.08	–0.05*
Yanzhou	1.20	0.04	1.19	0.02	1.23	0.06	1.11	0.00	1.14	–0.02
S_{WS}										
Beijing	0.34	0.02**	0.22	0.02*	0.38	0.02**	0.23	0.01	0.19	0.02*
Shijiazhuang	0.27	0.01	0.18	0.00	0.30	0.02	0.20	0.00	0.15	0.01
Xinxiang	0.21	0.02**	0.15	0.02	0.25	0.03**	0.17	0.03**	0.12	0.02*
Xuzhou	0.19	0.00	0.15	0.01	0.22	0.00	0.15	0.01	0.12	0.00
Yanzhou	0.20	0.00	0.14	0.00	0.24	0.00	0.15	0.01	0.10	–0.01

S_{SR}, sensitivity coefficient for solar radiation; S_{RH}, sensitivity coefficient for relative humidity; S_{Tmin}, sensitivity coefficient for minimum temperature; S_{Tmax}, sensitivity coefficient for maximum temperature; S_{WS}, sensitivity coefficient for wind speed. These sensitivity coefficients are indices without units.

* and ** represent linear coefficients significant at $p < 0.05$ and $p < 0.01$, respectively.

Xinxiang stations. Sensitivity coefficients of temperatures (S_T) increased in Beijing, Xinxiang, Xuzhou and Yanzhou stations, while it decreased in the Shijiazhuang station. The increase of S_T mainly occurred from seeding to jointing stages and heading to maturity stages in the Xinxiang station, with a statistically significant increase at the $p < 0.01$ level of significance. Decreases in sensitivity coefficients to temperatures were detected in the Shijiazhuang station and it mainly occurs from seeding to jointing stages and jointing to heading stages of winter wheat. It can be concluded that the fluctuation of temperature had a more positive effect on ET_c in Beijing, Xinxiang, Xuzhou and Yanzhou stations, which means that the increase in temperatures may lead to a greater increase of ET_c in these four stations. Sensitivity coefficients of wind speed (S_{WS}) increased significantly in

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Beijing and Xinxiang stations, with statistically significant increases at the $p < 0.01$ level of significance. With the decrease of WS, ET_c will decrease due to the positive coefficient. Trends of S_{RH} showed no significant changes in the time series analysis.

4.3.5 Variation of precipitation deficit and regional response to climate change

The precipitation deficit series of phenological phases at each station were detected with the purpose of appreciating the temporal variability of precipitation deficit changes and their magnitudes. As described in Table 4.7, the mean value of precipitation deficit in the whole growth stage is from −395.2 mm to −274.2 mm, with the minimum value detected at the Beijing station and the maximum value at the Xuzhou station. In the whole growth stage of winter wheat it was only at the Xinxiang station that a significantly decreasing trend was observed, with a slope of −2.01 mm year^{-1}; in other words, where the problem of water shortage becomes more severe. The precipitation deficit accounts for around 44.7% in the total precipitation deficit in seeding to jointing stage for five stations, followed by heading to maturity stages and jointing to heading stages. Moreover, the precipitation deficit increases significantly with the magnitude of 1.60 mm year^{-1} from seeding to jointing stages in the Beijing station. On the other hand, the precipitation deficit decreases significantly with the magnitude of −1.80 mm year^{-1} from the heading to maturity stages in the Xinxiang station.

As described in Table 4.8, the analysis of responses of precipitation deficit to climate change in different phenological phases was carried out in the selected weather stations. A negative relationship was found between precipitation deficit and SR and WS, which means that the increase in SR and WS had occurred with aggravation of precipitation deficit. Temperature in most stations showed a negative correlation to precipitation deficit, except minimum temperature in the Xuzhou and Yanzhou stations. A positive relationship was detected between precipitation deficit and RH, and RH was considered the most correlative factor to precipitation deficit, followed by SR, temperature and WS. A higher correlation was especially found in the heading to maturity stages of winter wheat between RH and precipitation deficit. As for SR, precipitation deficit in seeding to jointing stages, jointing to heading stages and heading to maturity stages of winter wheat showed a higher correlation with SR. A negative correlation was detected between temperature and precipitation in most stations, except minimum temperature in the Xuzhou and Yanzhou stations, in which stations a positive correlation was found, especially in sowing to seeding stages and seeding to jointing stages of winter wheat. The fact that the highest value for correlation coefficient of WS was detected as described in Table 4.8 indicates that WS is responsible for precipitation deficit of winter wheat.

Table 4.7. Long-term trends over the entire studied period of precipitation deficit (mm) in different phenological phases for the selected weather stations.

	Sowing to maturity		Sowing to seeding		Seeding to jointing		Jointing to heading		Heading to maturity	
Station	Mean	Slope	Mean	Slope	Mean	Slope	Mean	Slope	Mean	Slope
Beijing	−395.15	0.72	−5.33	0.00	−246.81	1.60*	−70.51	−0.31	−72.50	−0.56
Shijiazhuang	−334.16	0.50	−3.60	−0.03	−159.23	0.71	−81.30	0.47	−90.04	−0.65
Xinxiang	−317.14	−2.01*	−0.66	−0.29	−129.28	−0.05	−83.04	0.14	−104.15	−1.80**
Xuzhou	−274.19	0.18	−2.10	−0.27	−87.89	1.45	−83.57	0.02	−100.62	−1.03
Yanzhou	−309.37	1.14	−2.29	0.09	−125.51	0.97	−76.94	0.54	−104.64	−0.45

* and ** represent linear coefficients significant at $p < 0.05$ and $p < 0.01$, respectively.

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4.4 Discussion and Conclusions

Changes in the meteorological variables are important factors in the assessment of crop water requirement with climate change. The simultaneous consideration of the effects of meteorological variables such as SR, temperature, RH and WS on the crop water requirement with climate change is necessary. The present chapter has quantified changes in a set of meteorological variables and in ET_c under the weather conditions of the 3H Plain during the last 29 years.

A clear drop in SR was detected, which is usually called global dimming, probably caused by man-made aerosols and other air pollutants that have changed the optical properties of the atmosphere, in particular those of clouds (Mozny *et al*., 2009; Espadafor *et al*., 2011). The value of RH in several stations in the 3H Plain decreased due to the decline of precipitation and these results are in agreement with those from previous studies, but the tendency is not serious. The maximum temperature and minimum temperature were observed to increase asymmetrically and the minimum temperature was more responsible for average temperature than maximum temperature increase. This agrees with the asymmetry of the increase in maximum and minimum temperatures pointed out by several researchers

Table 4.8. The response of precipitation deficit (PD) to climate change in different phenological phases.

Station	Sowing to maturity	Sowing to seeding	Seeding to jointing	Jointing to heading	Heading to maturity
Solar radiation (MJ m^{-2} year^{-1})					
Beijing	–0.39	0.12	–0.70	–0.83	–0.39
Shijiazhuang	–0.50	–0.16	–0.46	–0.68	–0.67
Xinxiang	–0.19	–0.15	–0.58	–0.53	–0.81
Xuzhou	–0.10	–0.53	–0.57	–0.16	–0.54
Yanzhou	–0.31	–0.63	–0.55	–0.73	–0.46
Relative humidity (%)					
Beijing	0.84	0.37	0.77	0.67	0.79
Shijiazhuang	0.82	0.46	0.79	0.73	0.83
Xinxiang	0.78	0.35	0.69	0.48	0.83
Xuzhou	0.81	0.56	0.86	0.84	0.80
Yanzhou	0.78	0.64	0.79	0.40	0.82
Minimum temperature (°C)					
Beijing	–0.17	0.13	–0.13	0.30	–0.05
Shijiazhuang	–0.03	–0.13	0.10	–0.10	–0.12
Xinxiang	–0.23	0.13	0.17	–0.06	0.36
Xuzhou	0.46	0.40	0.60	–0.16	0.11
Yanzhou	0.46	0.55	0.52	0.34	0.43
Maximum temperature (°C)					
Beijing	–0.43	–0.07	–0.39	–0.02	–0.51
Shijiazhuang	–0.59	–0.38	–0.46	–0.56	–0.36
Xinxiang	–0.45	–0.24	–0.25	–0.25	–0.17
Xuzhou	–0.09	–0.02	0.01	–0.37	–0.39
Yanzhou	–0.20	–0.23	–0.12	0.13	–0.28
Wind speed (m s^{-1})					
Beijing	–0.56	–0.03	–0.58	–0.34	–0.47
Shijiazhuang	–0.47	–0.43	–0.53	–0.48	–0.51
Xinxiang	–0.54	0.27	–0.32	–0.18	–0.57
Xuzhou	–0.08	0.31	–0.12	–0.29	0.06
Yanzhou	–0.25	–0.01	0.04	–0.40	–0.21

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(Karl *et al.*, 1993; Easterling *et al.*, 1997; IPCC, 2007). The increase in the minimum temperature was higher and statistically more significant from seeding to jointing stages, with 0.57°C 10 year^{-1}. This is partially in agreement with the findings of Brunet *et al.* (2007), which indicate that the greatest contribution to the higher annual warming was winter and summer over the period 1901–2005. Due to the decreases in SR and RH, and the increase in the temperatures, a decrease in ET_c for the selected weather stations was detected in the whole growth stage of winter wheat. ET_c in seeding to jointing stages was observed with a significantly decreasing trend in the stations selected, while in the heading to maturity stages of winter wheat, the ET_c increased in the time series.

Sensitivities of ET_c to five major climatic variables were studied in the 3H Plain using a 29-year data set. Long-term average sensitivities were analysed in different phenological phases of winter wheat. This chapter showed that temperature was the most sensitive variable in general for the plain, followed by SR, WS and RH. However, this contrasts with the results of Gao *et al.* (2006) and Wang *et al.* (2007). They pointed to SR reduction along with WS as the main contributing variables in the year. From the results obtained in this chapter, changes in meteorological variables and their sensitivities may lead to different results on ET_c. The variability of the sensitivity coefficients indicated that the response of ET_c of winter wheat in the 3H Plain to climate change will differ with location and phenological phases. The decrease of S_{SR} mainly occurred from seeding to jointing stages and from heading to maturity stages of winter wheat. S_T increased in Beijing, Xinxiang, Xuzhou and Yanzhou stations, while it decreased in the Shijiazhuang Station. Fluctuation of temperature had a more positive effect on ET_c in Beijing, Xinxiang, Xuzhou and Yanzhou stations, which means that increase in temperature may lead to a greater increase of ET_c in these four stations. With the decrease of WS, ET_c will decrease due to the positive coefficient in Beijing and Xinxiang stations. Trends of S_{RH} showed no significant changes in the time series analysis.

The precipitation deficit series of phenological phases at each station were observed for the purpose of appreciating the temporal variability of precipitation deficit changes and their magnitudes. The precipitation deficit increases significantly with the magnitude of 1.60 mm year^{-1}, probably due to the decline of SR by 201.5 MJ m^{-2} 10 year^{-1} from seeding to jointing stages in the Beijing station. In contrast, the precipitation deficit decreases significantly with a magnitude of −1.80 mm year^{-1} due to the decline of RH by −1.64% 10 year^{-1} from heading to maturity stages in the Xinxiang station. A positive relationship was detected between precipitation deficit and RH, and RH was considered the most correlative factor to precipitation deficit.

A local/regional adjustment would be required for other areas, mainly with climate conditions differing substantially from those of the present chapter. From these ET_c estimates and temporal knowledge of precipitation deficit, irrigation schedules can be defined with the climate change. With the results provided in this chapter, agronomic effects due to changes in ET_c could be inferred for irrigated agriculture in the 3H Plain. In addition, the crop cycle is expected to be modified due to changes of weather and crop water requirement. For example, in Spain, Döll (2002) has estimated a decrease in irrigation requirements for 2020 due to the possibility of sowing earlier in time when the temperature regime is more favourable (higher temperatures). Additionally, results of this chapter can be used as a theoretical basis for partial derivative in future research on the response of crop water requirement to climatic change. Under the condition of the future climate scene data considered, further analyses on the agronomic consequences of climate change in semi-arid environments such as that found in the 3H Plain are in process, with the studying of interactions of the different components in determining crop irrigation requirements and yield. Lv *et al.* (2013) conducted the responses of winter wheat phenology, spatial variation of potential and rainfed production, actual evapotranspiration and irrigation water use efficiency to

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climate change with the WheatGrow model in China's main wheat production regions and further described impacting factors for improvement of wheat yield under climate change projections of A2, A1 and B1 in the 3H Plain. Furthermore, in the research of Liu, S. *et al*. (2010), the effects of climate change on grain production of a winter wheat–summer maize cropping system were investigated, corresponding to the temperature rising 2°C and 5°C, precipitation increasing and decreasing by 15% and 30%, and atmospheric CO_2 enriching to 500 ppmv and 700 ppmv (parts per million by volume) in the 3H Plain.

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