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Impacts of Climate Change on Water Requirements of Winter Wheat over 59 Years in the Huang-Huai-Hai Plain

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Abstract

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Daily data from 40 meteorological stations in the Huang-Huai-Hai Plain from 1955 to 2013 were analyzed using the Mann-Kendall test and partial correlation to determine the temporal trends of meteorological factors and their impacts on water requirements of winter wheat in different growing periods. Results showed that water requirements during the whole growing period in the Huang-Huai-Hai Plain were between 374 and 485.2 mm with an average of 412 mm in the past 59 years. In general, the value declined by 4 mm per decade. The distribution was ribbon-like, decreasing from the N to the S. Average wind speed, humidity, and sunshine hours declined significantly (α = 0.01, 0.05, and 0.01, respectively). Average vapour pressure and temperature increased significantly (α = 0.01). Only rainfall in Dongtai, Gaoyou, and Zhumadian could meet the water requirement of winter wheat over the whole growing period. Response of crop water requirement (ET_c) to meteorological factors change was linear and the order of impact on ET_c was vapour pressure, temperature, wind speed, and sunshine hours, while humidity had little impact on ET_c. Among the impacting factors, vapour pressure was in positive relation with ET_c.

Keywords: Mann-Kendall test; response of ET_c; crop water requirement

Global climate change has been an issue of wide concern to national governments, research institutions, and the public. The climate of China has changed significantly in recent years, with a nationwide trend of 21 consecutive warm winters from 1986 to 2006, and an increase in frequency and intensity of extreme climate events and disasters; climate warming has had many significant effects on natural ecosystems and biological systems on the global scale (IPCC 2007). The change of climate and its impacts on water security and agricultural production have intensified. In recent years, numerous reports have provided various assessments of the potential impacts of climate change on world water resources (Shiklomanov 2000; Arnell 2004; Shen *et al.* 2008). In China, concern over the impacts of climate change on water security is also rising (Zhang *et al.* 2007; Liu *et al.* 2010; Ma *et al.* 2010). One way to address these issues is through quantitative modelling. For example, the impact of climate change on irrigation water was modelled and mapped using a combination of crop and geographic information systems in the Guadalquivir River Basin in Spain (Rodriguez *et al.* 2007). Another research dealt with the impacts of climate change on the UK water sector (Wade *et al.* 2013). The possible implications of climate change on crop water requirements were also investigated in Atl-Jouf, Saudi Arabia (Chowdhury *et al.* 2013). Winter wheat and summer maize were selected to assess changes in water requirements and meteorological factors in the corresponding growing period near Guanzhong and to analyze the impacts of climate change on water requirements (Cao *et al.* 2008). The Penman-Monteith formula was adopted to calculate water requirements of rice in the Yangtze River Basin and to consider the impacts of climate change (Song *et al.* 2011). The increment scenario method analyzes the effects of temperature and

doi: 10.17221/164/2014-SWR

rainfall change on water requirements assuming that they change within a certain range. Studies of Liu *et al.* (2005) on the impacts of climate warming on water requirements of main crops in North China assumed temperature increase of 1–4°C in the future. They showed that effects of climate warming on water requirements differ among crops. In computer simulation studies, global climate models can be used to simulate climatic conditions and study the impacts of climate change on crop water requirements. Different Generation Circulation Models (GCMs) and Crop Estimation through Resources and Environment Synthesis (CERES)-Rice crop growth models were combined to investigate the relationship between rice water requirements and climate warming in China and evaluate the probability of future changes in rice water requirements (Cong *et al.* 2008).

The Huang-Huai-Hai Plain stretches between 113°00'E and the eastern coast, and 32°00'N–40°30'N, with a total area of 38.7 × 10^4 km^2. It covers about 30% of the Chinese plain and the cultivated area forms 1/6 of Chinese farmland and winter wheat planting area covers 32% of that of China. The per capita water resource is below 500 m^3 (which indicates extreme scarcity according to the United Nations) and is less than 1/3 of the national average. Rapid population growth, economic development, ecology and environmental protection will further increase water requirements. In the meantime, climate change will aggravate the trends of reducing available water resources seriously impacting long-term grain production, which poses a potential threat to the food security of China. In view of the key role of the Huang-Huai-Hai Plain in the food security of China and its sensitivity to climate change, research on the impacts of climate change on water requirements in the Huang-Huai-Hai Plain is of utmost importance.

MATERIAL AND METHODS

Daily data from 40 standard meteorological stations in the Huang-Huai-Hai Plain were obtained. The data included daily average air temperature, average relative humidity, average wind speed, sunshine hours, average vapour pressure, rainfall, and geographic information such as longitude, latitude, and altitude. All meteorological data were extracted from the China meteorological data sharing service system (http://cdc.cma.gov.cn/home.do). For missing or unreasonable data, kriging (ESRI 2008) interpolation was employed using data from adjacent sites, and a sequential data set of meteorological factors from 40 stations was finally established (station distribution is shown in Figure 1). The corresponding time series data for winter wheat were from the years 1955 to 2013.

Crop water requirements. The crop water requirement refers to the total water needed by a crop to get the highest yield under the conditions that water is abundant and other factors are not limiting. The "reference crop evapotranspiration multiplied by crop coefficient method" recommended by the FAO is the most common method used to calculate the water requirement of crops (Allen *et al.* 1998). The calculation formula is as follows:

$$ET_c = K_c \times ET_0 \qquad (1)$$

where:
ET_c – crop water requirement (mm)
K_c – crop coefficient
ET_0 – reference crop evapotranspiration (mm) calculated by the formula of Penman-Monteith

The crop growth stage coefficient (K_c) is defined as the ratio of ET_c to ET_0 (Jensen *et al.* 1990; Allen *et al.* 1998) for winter wheat. The values were 0.7, 1.15, and 0.3 at the initial stage, mid-season, and the late season, respectively.

Mann-Kendall test. The non-parametric Mann-Kendall (M-K) test (Mann 1945; Kendall 1975) has been widely used for trend detection in hydrologic and meteorological data. Its basic principle is that $U(d_1)$, the statistics of the trend test of the sequence $X_t = (x_1, x_2,..., x_n)$, is a parameter related to the sequence length *n*. $U(d_1)$ rapidly converges to the normal distribution when *n* is increasing. $U_{\alpha/2}$ is

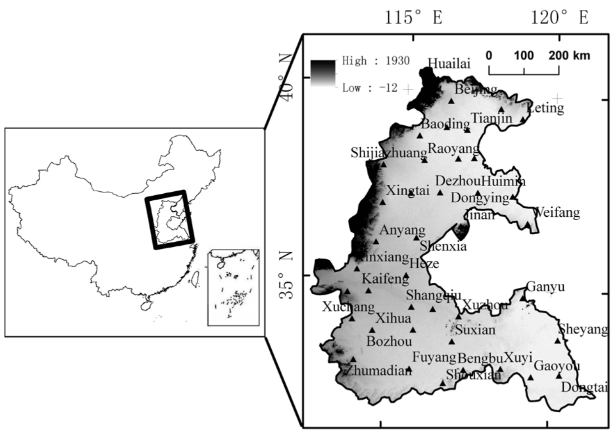

Figure 1. Location of meteorological stations in the Huang-Huai-Hai Plain

doi: 10.17221/164/2014-SWR

the threshold in the normal distribution table under the supposed significance level. If $|U(d_1)| < U_{\alpha/2}$, the trend is insignificant; otherwise it is significant.

The M-K test is largely used and it was found to be an excellent tool for trend detection in different climatic and hydrological data series (Chen *et al.* 2006; Xu *et al.* 2006a, b; Wang *et al.* 2007, 2012; Tabari *et al.* 2013). The World Meteorological Organization has also suggested using the M-K test for assessing trends in meteorological data (WMO 1988).

Rainfall and water requirements. The degree of coupling between crop water requirements and natural rainfall is between 0 and 1, which can be calculated using the following formula (Zhang *et al.* 2007; Yang *et al.* 2011):

$$\lambda_i = \begin{cases} 1 & (P_i \geq ET_{ci}) \\ P_i/ET_{ci} & (P_i < ET_{ci}) \end{cases} \quad (2)$$

where:

λ_i – degree of coupling between crop water requirements and natural rainfall in the i^{th} stage

P_i – natural rainfall (mm) in the i^{th} stage

ET_{ci} – crop water requirement (mm) in the i^{th} stage

RESULTS AND DISCUSSION

Change trends and spatial distribution of crop water requirements

Temporal characteristics of water requirements. A simple linear regression with the water requirement as the dependent variable and time as the independent variable (Figure 2a) described the process of the changing annual average water requirement of winter wheat in the Huang-Huai-Hai Plain from 1955 to 2013. As can be seen from the figure, the annual average value of the whole area fluctuated between 374.2 and 485.2 mm, generally showing a significant downward trend with a tendency rate of –4 mm per decade (α = 0.01 confidence level). UFK statistics in Figure 2b showed that the water requirement increased before 1980, especially from 1970 to 1980, and reached a peak in 1980; however, after 1980 it began to decline continuously. The abrupt change occurred in 1980. The decline was evident in 29 out of the 40 stations (Figure 2c). Of the stations showing decline, by most of them (15 stations) the decline was significant at a confidence level of α = 0.01, by a few (2 stations) the significance level was α = 0.05, and by the remaining 12 stations the decline was insignificant. By contrast, 11 stations exhibited an increasing trend. Four of these stations reported a significant decline at the level of α = 0.01 and the remaining 7 stations insignificant. The average water requirement of the whole growing period was about 412 mm, with the maximum in Beijing and the minimum in Xihua. As for the inter-decadal variation, the 1960s average was 424.6 mm, which increased by 22 mm in the 1970s. This was followed by declines of 21.3 mm from the 1980s to the 1990s, of 6.3 mm from the 1990s to the 2000s, and of 18.4 mm from the 2000s to the first 10 years of the 21st century.

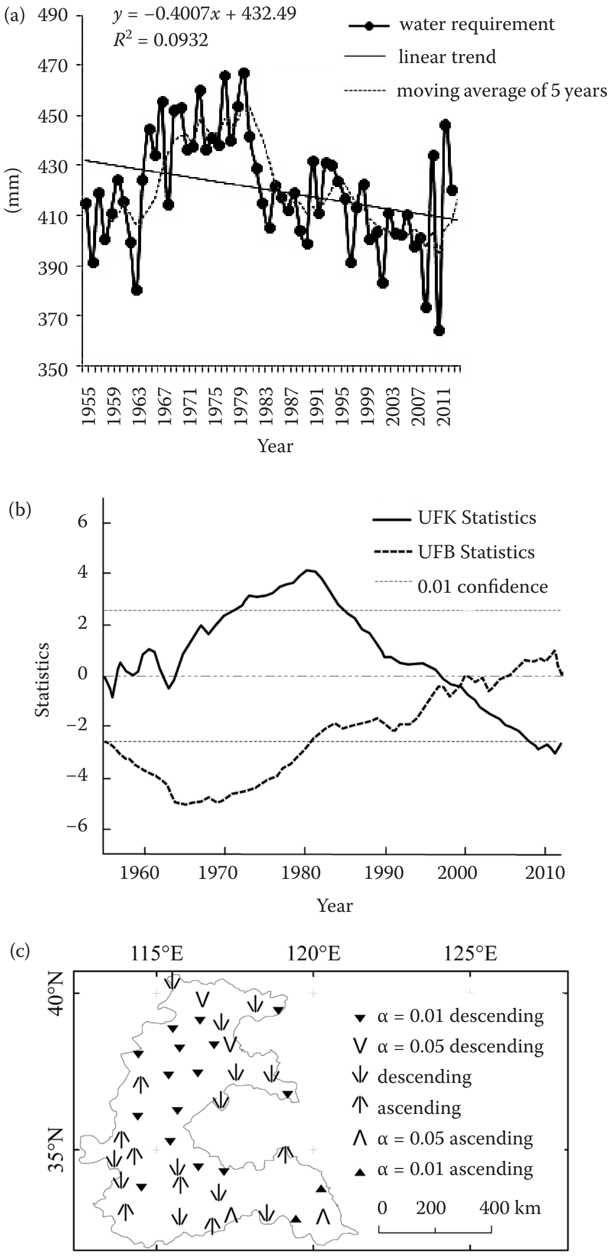

Figure 2. Water requirements trend distributions for the whole growing period: linear trend (a), mutation test (b), distribution of Z statiscitcs (c)

doi: 10.17221/164/2014-SWR

Spatial distribution of water requirements. Spatial distribution of multiannual values for water requirements are shown in Figure 3. The value in the sowing to overwintering period was the lowest out of the four stages; the regional difference ranged from 48.6 to 59.1 mm with an average of 54.1 mm, which suggested that spatial variation within this stage was low. It had a band-like distribution and decreased gradually from the SE and NE to the middle of the area. Turning green to jointing phase was the most water demanding period, having values of 137.9–173.3 mm with an average of 157.5 mm. This growing period lasted 140 days and daily water demand was 1.1 mm. It generally presented a declining trend from the N and SE to the north central area. The data from jointing to flowering period ranged from 80.1 to 136.6 mm with an average of 102.2 mm. The highest values, exceeding 110 mm, were generally noted in the NE, whereas the lowest values were noted in the SE and SW. The growing period lasted 40 days and the mean daily value was 2.6 mm. During the period from flowering to ripening, the corresponding values were 80.1–124.2 mm with an average of 102.2 mm. The NE had the highest values and the SE and SW had the lowest. The growing period lasted 30 days and the daily average was 3.4 mm, which was the maximum daily water requirement. On an annual basis, areas with the highest water requirement were in the N and those with the lowest were in the W, SW, and SE. The distribution was ribbon-like and decreased from the N to the S.

It can be concluded that except for the turning green to jointing period, the spatial distribution of each growing stage exhibited the same pattern as that of the whole growing period. Comparing the water requirement of winter wheat at each growing stage showed that although the crop coefficient of flowering to ripening stage was low, its daily water requirement was the highest because of its highest daily potential evapotranspiration. The water requirement of the growth stage from jointing to flowering was the second highest, and that of the growth stage from sowing to overwintering was the lowermost.

Degree of coupling between water requirements and precipitation. The degrees of rainfall coupling

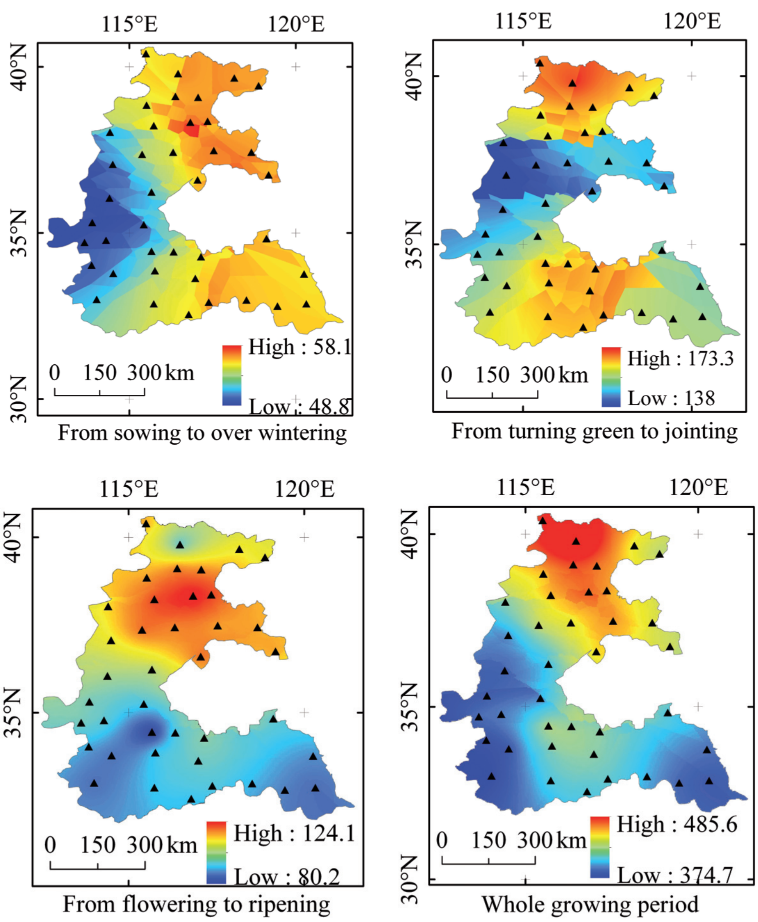

Figure 3. Average water requirements distributions in the growing period of winter wheat

doi: 10.17221/164/2014-SWR

at four growing stages and the whole growing period of winter wheat at each station were calculated on the basis of rainfall and water requirements (Table 1). Regardless of irrigation, the rainfall registered by Gaoyou, Dongtai, and Zhumadian stations met the water requirement of the whole growing period, whereas that recorded by Bengbu and Zhumadian met the water requirement from sowing to overwintering. Rainfall at Dongtai, Gaoyou, Sheyang, and Xuyi met the water requirement of the turning green to jointing period, and that at Dongtai and Gaoyou met the water requirement of the jointing to flowering period, but no station record met the water requirement of the flowering to ripening period, which had the greatest daily water requirement. The degree of coupling and the spatial distribution of water requirements indicated that the region with a low degree of coupling had high water requirements. For this reason, effective measures should be taken reflecting the characteristics of water requirements and precipitation during different stages of winter wheat growth. In regions requiring irrigation it is important to supply water timely and properly in order to ensure high and stable yields of wheat.

Analysis of climatic change effects on water requirements

Changing trends of meteorological factors. Crop water requirements were influenced mainly by climate factors and change trends. Accordingly, the impact of climate fluctuations reflected the comprehensive effects of various factors. The M-K test was conducted on several factors (wind speed, vapour pressure, temperature, sunshine hours, and relative humidity) influencing the water requirement of winter wheat. The sequential values of Z statistics, derived from the progressive analysis of the M-K rank correlation, are described in Figure 4 and the inter-decadal variation is shown in Table 2. The trend of daily average wind speed for 40 stations in the Huang-Huai-Hai Plain from 1955 to 2013 declined sharply and was highly significant at 38 stations ($\alpha = 0.01$). It decreased continuously from 3.33 m/s in the 1950s to 2.43 m/s

Table 1. The degree of coupling between rainfall and water requirements of winter wheat

Station	Periods					Station	Periods				
	A	B	C	D	E		A	B	C	D	E
Anyang	0.39	0.67	0.36	0.31	0.39	Leting	0.31	0.49	0.22	0.27	0.39
Bengbu	0.93	1.00	0.99	0.85	0.82	Nangong	0.27	0.49	0.24	0.21	0.26
Baoding	0.25	0.46	0.20	0.21	0.26	Raoyang	0.24	0.42	0.19	0.20	0.25
Beijing	0.17	0.32	0.07	0.27	0.38	Shangqiu	0.47	0.58	0.31	0.64	0.92
Bozhou	0.64	0.73	0.63	0.59	0.66	Sheyang	0.88	0.78	1	0.82	0.79
Cangzhou	0.23	0.37	0.19	0.22	0.24	Shijiazhuang	0.32	0.54	0.28	0.24	0.35
Dangshan	0.59	0.68	0.59	0.52	0.60	Shouxian	0.90	0.81	0.93	0.97	0.85
Dezhou	0.31	0.55	0.27	0.30	0.27	Suxian	0.69	0.70	0.73	0.66	0.66
Dongtai	1	0.85	1	1	0.98	Tangshan	0.28	0.51	0.21	0.23	0.32
Dongying	0.35	0.50	0.36	0.29	0.32	Tianjin	0.29	0.53	0.21	0.25	0.32
Fuyang	0.85	0.83	0.87	0.82	0.87	Weifang	0.38	0.55	0.42	0.30	0.32
Ganyu	0.68	0.68	0.67	0.67	0.69	Xihua	0.77	0.99	0.75	0.68	0.76
Gaoyou	1	0.94	1	1	0.93	Shenxian	0.40	0.70	0.35	0.32	0.41
Heze	0.51	0.75	0.49	0.43	0.50	Xinxiang	0.41	0.68	0.35	0.36	0.42
Huailai	0.17	0.32	0.11	0.16	0.21	Xingtai	0.23	0.42	0.15	0.19	0.29
Huanghua	0.27	0.46	0.21	0.23	0.28	Xuyi	0.96	0.86	1	0.90	0.81
Huimin	0.30	0.47	0.22	0.26	0.35	Xuzhou	0.63	0.73	0.63	0.57	0.65
Jinan	0.35	0.52	0.30	0.29	0.40	Xuchang	0.68	0.91	0.61	0.61	0.75
Kaifeng	0.49	0.69	0.45	0.44	0.50	ZhengZhou	0.52	0.78	0.46	0.48	0.52
Langfang	0.20	0.46	0.16	0.17	0.20	Zhumadian	1.00	1	0.97	0.93	0.99

A – whole growing; B – from sowing to over wintering; C – from turning green to jointing; D – from jointing to flowering; E – from flowering to ripening

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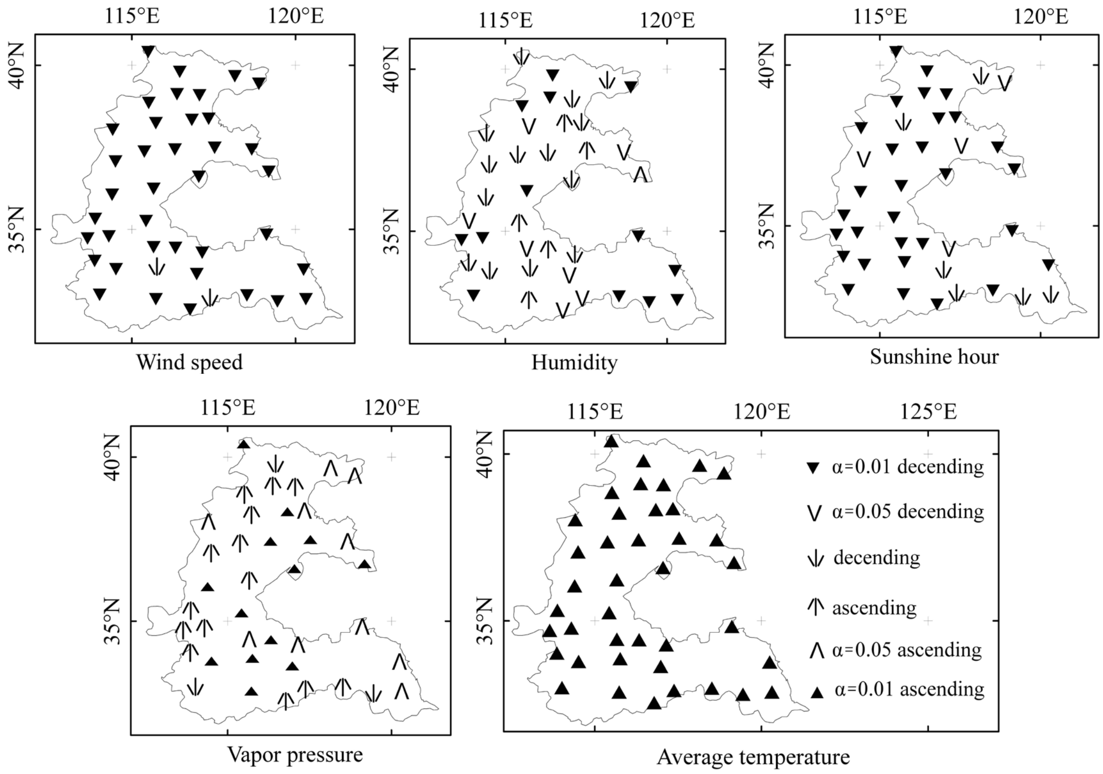

Figure 4. Change trends for meteorological factors

at a rate of –0.19 m/s per decade. A descending trend in overall average humidity was detected; the trend was highly significant at 13 stations (α = 0.01), significant at 7 stations (α = 0.05), and insignificant at 14 stations. In contrast, 6 stations had increases (only one was significant at α = 0.05 level). The average value of the whole area indicated a significant decline (α = 0.05). Humidity declined from the 1950s to the first 10 years of the 21st century at a rate of –0.65% per decade, and the decline in average relative humidity was consistent with the rise in global temperature. All stations reported a decline in sunshine hours, by 31 of which the decline was highly significant (α = 0.01), by 3 it was significant (α = 0.05), and by 6 stations it was insignificant; the latter tended to be in the SE and NE parts of the study area. The average of the whole area indicated a highly significant decline (α = 0.01). The number of sunshine hours dropped from 6.79 h/day in the 1950s to 5.91 h/day in the early 21st century, declining at a rate of –0.19 h/day/decade. The trend in daily average vapour pressure was increasing (α = 0.05), with a slight decline at 3 stations, and a decrease at the other stations. Ten stations reported significant (α = 0.05) and 13 stations highly significant (α = 0.01) increases. Vapour pressure increased in the 20th century; it rose from 7.36 hPa in the 1950s to 7.94 hPa in the 1990s. Then it dropped to 7.82 hPa after the turn of the 21st century. Average temperature was the meteorological factor that showed a marked change. All stations presented

Table 2. Change trends for different meteorological factor means in the Huang-Huai-Hai Plain

Decade	Wind speed (m/s)	Humidity (%)	Sunshine (h/day)	Vapour pressure (hPa)	Average temperature (°C)	Precipitation (mm)
1955–1959	3.33	65.8	6.79	7.36	7.24	214.8
1960–1969	3.26	64.7	6.76	7.58	7.57	212.5
1979–1979	2.99	64.7	6.56	7.59	7.73	202.7
1980–1989	2.67	63.8	6.35	7.63	7.84	205.5
1990–1999	2.62	64.7	6.09	7.94	8.49	218.7
2000–2013	2.43	62.1	5.91	7.82	8.80	218.3

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a distinctive and continuous trend of rising average temperature that was significant at α = 0.01 confidence level. It increased by 21.55% in 59 years, which is consistent with global warming trends. It rose by 0.33, 0.16, 0.11, 0.65, and 0.41°C in the 10-year periods considered here. The average value for the whole area was 0.3°C per decade. Precipitation during the whole growing period indicated a decline from the 1950s to the 1970s followed by an increase from the 1980s to the 2010s. This result is consistent with studies of Yang *et al.* (2013).

Response of water requirements to climate change. Changes in the water requirement of winter wheat were affected mainly by meteorological factors, such as solar radiation, temperature, sunshine hours, average relative humidity, rainfall, cloud amount, and wind speed. In this paper, five meteorological factors (average air temperature, sunshine hours, average wind speed, relative humidity, average vapour pressure) and four stations (Beijing, Anyang, Shouxian, Weifang) located in the N, in the Middle, in the S, and in the E of the area, respectively, were selected to analyze the impact of climate factors on water requirements in the whole growing period of winter wheat. Wind speed, sunshine hours, and humidity showed a downward trend but vapour pressure and temperature showed an upward trend in the Huang-Huai-Hai Plain (Figure 4). So the change steps of wind speed, sunshine hours, humidity, and vapour pressure were –10% by each, and the change step of temperature was +0.5°C, based on the daily monitored data during the whole growing period of winter wheat. Results showed that the change of relative humidity had little impact on the water requirement change. Response of water requirement to different meteorological factors in different areas is shown in Figure 5. The relation between the change of the four meteorological factors and ET_c was almost linear, and wind speed, sunshine hours, temperature were in a positive but vapour pressure was in a negative relation with ET_c. Vapour pressure had the largest impact on ET_c, followed by temperature, wind speed, and sunshine hours; the same factor had different impact on ET_c at different stations. Figure 5a indicates that a 0.5°C temperature rise resulted in the winter wheat ET_c increase by 5.0, 5.4, 7.5, 5.8, and 6.9% in Beijing, Anyang, Shouxian, Weifang, and the whole plain, respectively, which could be regarded as the

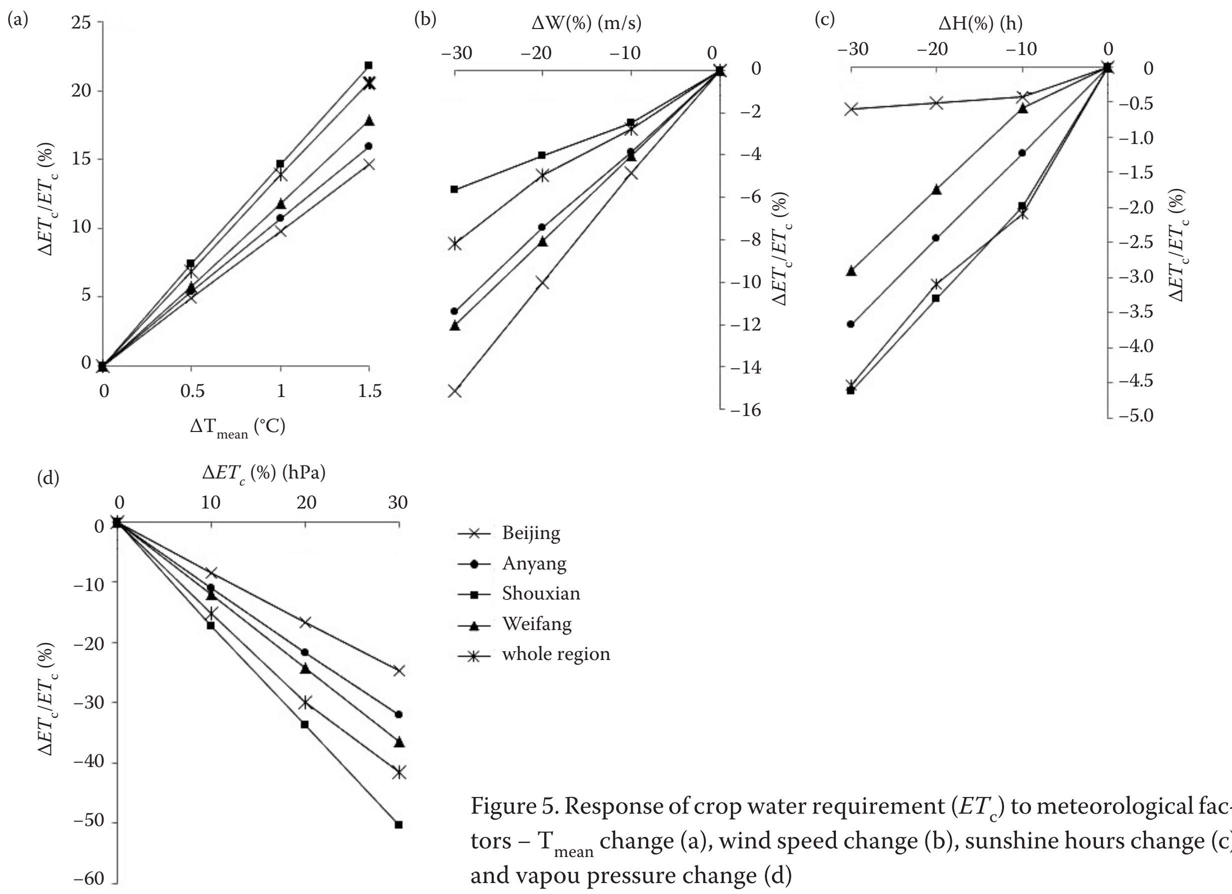

Figure 5. Response of crop water requirement (ET_c) to meteorological factors – T_{mean} change (a), wind speed change (b), sunshine hours change (c) and vapou pressure change (d)

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impact of temperature on ET_c increasing from the N to the S, from the W to the E in the Huang-Huai-Hai Plain. Figure 5b shows ET_c lowering by 4.9, 3.8, 2.5, 4.1, and 2.8% in Beijing, Anyang, Shouxian, Weifang, and the whole plain, respectively, in the case of wind speed decrease by 10%. The impact of wind speed on ET_c is decreased from the N to the S, from the W to the E. Figure 5c indicates ET_c decrease by 0.43, 1.22, 2.0, 0.58, and 2.1% in Beijing, Anyang, Shouxian, Weifang, and the whole region, respectively, in the case of sunshine hours decrease by 10%. Figure 5d illustrates ET_c decrease by 8.5, 11.1, 17.3, 11.9, and 15.2% in Beijing, Anyang, Shouxian, Weifang, and the whole region in the case of vapour pressure increase by 10%. The difference with respect to location was identical both for vapour pressure and temperature.

The change of meteorological factors and their interaction leading to the decrease of ET_c in the plain should be subject to further research exceeding the possibilities of our independent study.

CONCLUSIONS

Temporal trend of the water requirement: The water requirement of winter wheat in the Huang-Huai-Hai Plain generally showed a declining trend during the 59 years studied. The average rate of decrease for the whole area was –4 mm per decade. The rate in the first, second, third, and fourth stage was –1.7, –3.8, –0.7, and –3.5 mm per decade, respectively. Except for the third period, water requirements of all stages, including the whole growing period, had a declining trend (α = 0.01 confidence level).

Temporal trend of climate factors: Average wind speed, humidity, sunshine hours decreased at a rate of –0.19 m/s, –0.65%, and –0.19 h/day per decade, respectively, of which sunshine hours declined continuously from 6.79 h/day in the 1950s to 5.91 h/day in the early 21st century. In general, the average vapour pressure rose in the 20th century from 7.36 hPa in the 1950s to 7.94 hPa in the 1990s, but dropped to 7.82 hPa after the turn of the 21st century. Average temperature increased by 21.55% in the course of the 59 years and the average value for the whole area was 0.3°C per decade.

Spatial distribution of the water requirement: The spatial distribution indicated that the highest values were detected in the N and the lowest in the SW and SE.

Degree of coupling between the water requirement and effective precipitation: Regardless of irrigation conditions, only the rainfall in Gaoyou, Dongtai, and Zhumadian could meet the water requirement of the whole growing period. In general, the areas with a low degree of coupling had high water requirements.

Response of water requirements to climate change: Results showed that response of water requirement to vapour pressure, temperature, wind speed, and sunshine hours reduced orderly and the change was basically linear between ET_c and meteorological factors. There was a positive relation between ET_c and vapour pressure and a negative relation with the other factors. ET_c would decrease by 8.5, 11.1, 17.3, 11.9, and 15.2% in Beijing, Anyang, Shouxian, Weifang, and the whole region in the case of vapour pressure increase by 10%. The interaction of factors causing the decrease of ET_c in the Huang-Huai-Hai Plain within 1955–2013 needs further research.

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