Effects of climate change on spring wheat phenophase and water requirement in Heihe River basin, China

DONGMEI HAN^{1,*}, DENGHUA YAN², XINYI XU¹ and YU GAO³

¹College of Water Sciences, Beijing Normal University, Beijing, China.

²State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100 038, People's Republic of China.

³Environmental Science and Engineering Department, Donghua University, Shanghai 201 620, People's Republic of China.

*Corresponding author. e-mail: h15176078383@163.com

Climate change has significantly altered the temperature rhythm which is a key factor for the growth and phenophase of the crop. And temperature change further affects crop water requirement and irrigation system. In the north-west of China, one of the most important crop production bases is Heihe River basin where the observed phenological data is scarce. This study thus first adopted accumulated temperature threshold (ATT) method to define the phenological stages of the crop, and analysed the effect of climate change on phenological stages and water requirement of the crop during growing season. The results indicated the ATT was available for the determination of spring wheat phenological stages. The start dates of all phenological stages became earlier and the growing season length (days) was reduced by 7 days under climate change. During the growing season, water requirement without consideration of phenophase change has been increased by 26.1 mm, while that with consideration of phenophase change was featured in the decrease of water requirement by 50 mm. When temperature increased by 1°C on average, the changes were featured in the 2 days early start date of growing season, 2 days decrease of growing season length, and the 1.4 mm increase of water requirement, respectively.

1. Introduction

Global climate has been experiencing a time of warming characterised change over the past century (IPCC 2007). This can be traced from the change of crop phenophase which in turn disrupts the balance between water supply and demand in agriculture (General Office of the State Council of the People 2008). The research of phenophase has been a hot issue for regional agricultural production, irrigation management and terrestrial ecosystems management (Feng *et al.* 2004; Xiao *et al.* 2007). In consideration of the unique geographical location (lack of phenological data) and important

status in agricultural production, Heihe River basin in the northwestern China was selected as study area. Crop phenophase can better reveal the responsive mechanism of crop water requirement to climate change, and also clarify the water requirement change mechanism under the impact of crop phenophase, which thus provides a scientific reference for the protection of food security and optimal water sources management in Ningxia, Gansu and Inner Mongolia.

Recent studies on climate change on crop growth phenophase have concentrated on the response of temperature to climate change. These studies usually took plenty of phenological observation data as

Keywords. Climate change; water requirement; accumulated temperature threshold; spring wheat; Heihe River basin.

reference and investigated crop phenophase change by analysing the thermal condition of crop growth. Although the research method adopted by these studies were extensively applied and proved in many fields (Rosenzweig *et al.* 1994; Mei *et al.* 1998; Jia and Gao 2009; Juan *et al.* 2009; Nelson *et al.* 2009), the application was limited to some extent in many areas without observed phenology data. With respect to crop water requirement under climate change, these studies tend to limit their research to three respects (Todico *et al.* 2007; Xiang *et al.* 2008; Feng *et al.* 2009; Ping *et al.* 2009), i.e., require a great number of phenological observational data, the impact of climate change on phenological stages and growing length of crop, and the impact of phenophase change on crop water requirement.

In this study, we aim to: (1) explore the applicability of accumulated temperature threshold (ATT) recorded in crop growing period to compensate the insufficiency of phenological observational data, (2) analyze the variation of the crop phenological stage and the crop growing season under the impact on climate change, and (3) simulate the quantity evolution of crop water requirement impacted by climate change. Thus, this study proposed a new approach to analyse crop phenophase during crop growing season in some regions without enough observed data and further simulate the crop phenophase change and crop water requirement with the increasing temperature.

2. Materials and methods

2.1 Study area

Heihe River basin is located at $\sim 98\text{--}102^\circ\text{E}$ and $\sim 37\text{--}42^\circ\text{N}$, and it is the second longest continental river in China, covering an area of $14,290\text{ km}^2$. The river originates from the Qilian Mountain in Qinghai Province, flowing through Qinghai Province and Gansu Province and ending in Inner Mongolia. On the upstream reaches of Heihe River, the annual mean temperature is less than 2°C and annual mean precipitation is close to 350 mm . On the middle reaches of Heihe River, the annual precipitation is only 140 mm , and annual mean temperature ranges from 6 to 8°C . While the annual sunshine duration ranges from 3000 to 4000 hrs , the annual evaporation is as high as 1410 mm (Yang *et al.* 2008; Wang *et al.* 2015). On the downstream reaches, the annual precipitation is only 47 mm , and with the annual sunshine duration being 3446 hrs , the annual evaporation is as much as 2250 mm (Yang *et al.* 2008; Wang *et al.* 2015).

Heihe River basin is a representative basin in the continental river basin, wherein irrigated agriculture is the main kind of agriculture. Wheat and maize are the main crops planted in the Heihe River basin, among which wheat accounts for more than 50% of all cereal crops in this area. The main planting areas are mostly distributed in the mid-stream of the basin like Jinta, Jiuquan, Zhangye.

Figure 1. Location and topography of the study area.

and Shandan (figure 1), so the middle reaches is one of the important bases of food and vegetable production in western China. Among the crops planted in the basin, wheat is sowed on around March 20th and harvested on around July 20th, with 120 days of growth period, generally. Looked from relevant provinces' local chronicles, the cultivation of wheat is the largest acreage and highest output in Heihe River basin during the 1980s and 1990s, especially in the intercropping pattern of wheat and maize. High crop water requirement and shortage of available water resources have reduced the crop acreage in recent years.

2.2 Data

In this study, the data were collected from three sources: meteorological data, including precipitation, wind speed, atmosphere pressure, relative humidity, average temperature, maximum and minimum temperature and number sunshine hours, were acquired from the China Meteorological Science Data Service. Then this paper collected from daily meteorological data from 15 meteorological stations during the period of 1961–2010 growing seasons. The phenology data, which was from China Crops Growth Information, including start date, end date of crop phenological stages and the growing season length, were obtained from the agriculture observatory during 1 January 1961–31 December 2010. And the digital elevation model

(DEM) were obtained from National Topographic Data in China.

2.3 Phenological stages division

The most suitable time for wheat sowing is when the daily average temperature is greater than 7°C (Jia and Gao 2009). Taking into account the actual weather condition of the research area, this study took the sliding average temperatures of 5 consecutive days as the index to define the start date and end date of the crop growing stage (Yan *et al.* 2011). Thus, an accumulated temperature (AT) greater than 10°C (given in table 1) was the beginning of wheat growing. When AT was up to 102°C, it was the start date of the wheat seedling stage, and the AT value was selected as the threshold of seedling stage. Similarly, 302°C was the threshold of wheat tillering stage, the temperature of AT identified for wheat jointing stage, heading stage and dough stage were 597, 977 and 1677°C, respectively (Lu and Wang 1965).

With regard to response to climate change, the result of temperature forecasting was more precise than other meteorological elements (Qing *et al.* 2007) (e.g., precipitation) and temperature is one of the key elements affecting crop growth. Therefore, this study took temperature mutation points as the basis of time division. In the Heihe River basin, abrupt changes in temperature measured by the Mann–Kendall method (Sheng *et al.* 2002) occurred in 1991, with significance test of $\alpha=0.05$ (figure 2). The contribution of climate change to temperature was variable. There was little change in temperatures during 1961–1991, yet there was a significant change during 1992–2010. Thus, this study defined the period 1961–1991 as the base period and 1992–2010 as comparison period 1 with the impact of climate change on crop phenophase. Also, in order to give a better illustration of the importance of the impact of phenophase change on

Table 1. The ATT greater than 10°C for different growth stages during the wheat growing season.

Crop	Stage	Threshold (°C)
Spring wheat	Sowing–seedling	102
	Seedling–tillering	200
	Tillering–jointing	295
	Jointing–heading	380
	Heading–dough	700

Figure 2. The trend of temperature analyzed by Mann–Kendall method.

crop water requirement, this study further defined the period 1992–2010 as comparison period 2, without consideration of phenological change.

2.4 Climatic tendency rate

To quantitatively analyse the variation of wheat phenophase, this study adopted the climate tendency rate (Li *et al.* 2011).

$$\theta_i = \frac{n \times \sum_{j=1}^n (j \times P_{ij}) - \sum_{j=1}^n j \times \sum_{j=1}^n P_{ij}}{n \times \sum_{j=1}^n j^2 - \left(\sum_{j=1}^n j \right)^2}, \quad (1)$$

where n is the number of years of analysed period; P_{ij} is the value of i th year of i th statistic characteristics; θ_i is the slope of i th statistic characteristics tendency curve; $\theta_i > 0$ indicates phenophase changes behind schedule and $\theta_i < 0$ indicates phenophase changes ahead of schedule.

2.5 Crop water requirement

Crop water requirement was calculated by the method of water balance, which also could be obtained by a comprehensive approach of climatology. As the great demand data required for applying water balance method is difficult to obtain, the comprehensive method is widely used. In this regard, reference is made to the formula recommended by the Food and Agriculture Organization of United Nations (FAO) for crop water requirement during the crop growing season (Allen *et al.* 1998; Yin *et al.* 2012):

$$ET_P = K_C \times ET_O, \quad (2)$$

where ET_P is the water quantity required by the crop (mm per day) with abundant water supply, K_C is the crop coefficient in different phenological phase, mainly referred to the result (table 2) calculated in the reference (Li *et al.* 2009), and ET_O , is the reference crop evapotranspiration (mm per day).

Table 2. Crop coefficient for different growth stages during the wheat growing season.

Crop	Stage	K_C
Spring wheat	Sowing–seedling	0.32
	Seedling–tillering	0.48
	Tillering–jointing	0.76
	Jointing–heading	1.05
	Heading–wax ripeness	0.84
	Growing season	0.84

The method to calculate ET_O was first put forward by Penman in 1948 (Penman 1948). After several modifications, this method was estimated and made to the formula recommended by FAO to simulate the ET_O (Allen *et al.* 1998; Mcvillar *et al.* 2012). Previous research results showed the simulation of the model was more accurate and had been widely used around the world. And the application of this model has been well in Heihe River basin based on the achievements from domestic and foreign scholars (Wang *et al.* 2012).

The Penman–Monteith equation as formulated by Allen *et al.* (1998) for the calculation of daily ET_O (mm per day) is

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma(900/(T_{\text{mean}} + 273))\mu_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)}, \quad (3)$$

where ET_O is the evapotranspiration (mm per day); T_{mean} is the average daily air temperature ($^{\circ}\text{C}$), R_n is the net radiation at the crop surface (MJm^{-2} per day); G is the soil heat flux (MJm^{-2} per day), 900 is the conversion factor, Δ is the slope of the vapor pressure curve ($\text{kPa} \cdot ^{\circ}\text{C}^{-1}$), γ is the psychrometric constant ($0.054 \text{ kPa} \cdot ^{\circ}\text{C}^{-1}$), μ_2 is the wind at 2 m height ($\text{m} \cdot \text{s}^{-1}$), and $(e_s - e_a)$ the vapour pressure deficit (kPa).

3. Results and discussion

3.1 Application of the accumulated temperature threshold method

It can be summarised from table 3, using the method of accumulated temperature threshold (ATT), that the simulated average sowing date of wheat was suitable from March 21 to 27 which varied no more than 4 days when compared with the observation (from March 25 to 30). The seedling date ranged from April 14 to 20, and the tillering date was from April 30th to May 6th, both of which were within the usual margins of error. Similarly, through the analysis of the jointing date, the heading date and the wax ripeness date calculated

Table 3. Comparative analysis the growth stages calculated by ATT and the observations (OBS).

Crop	Stage	ATT	OBS
Spring wheat	Sowing	3/21~3/27	3/25~3/30
	Seedling	4/14~4/20	4/18~4/23
	Tillering	4/30~5/6	5/5~5/10
	Jointing	5/15~5/21	5/24~5/29
	Heading	6/5~6/11	6/13~6/18
	Wax ripeness	7/22~7/28	7/17~7/22

by ATT, all of the errors were within the regulated criteria of error.

Therefore, the ATT method was applicable for the division of phenological stages during the growing season. In the following sections, this study adopted the approach of ATT to evaluate the impact of climate change on change of phenological stages and water requirement for spring wheat during the base period, comparison period 1 and comparison period 2, respectively.

3.2 Impacts of climate change on phenological stages for spring wheat

This section mainly analysed the effects of climate change on the phenological stages and the growing season length of spring wheat. In terms of the phenological stages, the results indicated that all of the beginning dates of phenological stages were advanced to different extents. According to above, sowing date during the base period was between March 25th and 27th with comparison period 1 advanced by 10 days on average, and sowing date of multi-year average was between March 17th and 19th. Seedling date during the base period was during April 22–24 with comparison period 1 advanced by 10 days on average, that was the same data as that of multi-year average. During the base period, the tillering stage, jointing stage, heading stage and wax ripeness stage were from May 8th to 10th, from May 28th to 30th, from June 17th to 19th and from July 20th to 21st, respectively, with comparison period 1 advanced by 12 days, 13 days, 14 days and 17 days, respectively (table 4).

For the length of the wheat growth period, days of different stages varied slightly over the comparison period 1 (affected by climate change), when compared with the base period. On an average, for many years, the days represented a slightly lower than those during the base period. According to that, under climate change, the sowing–seedling stage and the tillering–jointing stage remained unchanged with 28 days and 18 days, respectively. However, the seedling–tillering stage, the jointing–heading stage and the heading–dough stage were shortened from 16, 22 and 32 days to 15, 19 and 29 days, respectively. Therefore, in the length of the wheat growing season, there was a 7-day reduction with the effects of climate change (table 5).

3.3 Impacts of climate change on water requirement for spring wheat

Based on the result from the previous section that the growing season length of spring wheat was shortened by 7 days, it can be inferred that the days of water requirement was also shortened by 7 days. Therefore, the water requirement of the growing season during comparison period 1 was decreased by 50 mm (11.5%) compared with that during the base period. Changes of water requirement at different stages showed that at the sowing–seedling stage, the value of wheat water requirement was 35.1 mm during the base period and that it decreased by 17.4% during comparison period 1. At the seedling–tillering stage, the value of wheat water requirement was 39.1 mm during the base period, and this decreased by 8.4%

Table 4. Variation of the phenological stages for spring wheat in different scenarios. The form of a/b represents month/day.

Crop	Stage	Base period	Comparison period 1	Multi-year average
Spring wheat	Sowing	3/25~3/27	3/15~3/17	3/17~3/19
	Seedling	4/22~4/24	4/12~4/14	4/12~4/14
	Tillering	5/8~5/10	4/27~4/29	4/28~4/30
	Jointing	5/28~5/30	5/15~5/17	5/17~5/19
	Heading	6/17~6/19	6/3~6/5	6/5~6/7
	Wax ripeness	7/20~7/21	7/2~7/4	7/6~7/8

Table 5. Variation of the length of phenological stages and growing season for spring wheat in different scenarios. The unit of every number is day(s).

Crop	Stage	Base period	Comparison period 1	Multi-year average
Spring wheat	Sowing–seedling	28	28	26
	Seedling–tillering	16	15	16
	Tillering–jointing	18	18	17
	Jointing–heading	22	19	21
	Heading–wax ripeness	32	29	31
	Growing season	116	109	111

Table 6. Water requirements of various phenological stages and growing season for spring wheat in different scenarios. The unit of number is mm.

Crop	Stage	Base period	Comparison period 1	Comparison period 2	Multi-year average
Spring wheat	Sowing–seedling	35.1	29.0	36.8	27.9
	Seedling–tillering	39.1	35.8	44.6	35.9
	Tillering–jointing	75.1	70.0	69.4	67.2
	Jointing–heading	138.4	110.2	130.2	123.1
	Heading–wax ripeness	147.1	139.9	179.9	147.5
	Growing season	434.8	384.7	460.9	401.6

during comparison period 1. Also, the decrease of water requirement at tillering–jointing stage, jointing–heading stage and heading–wax ripeness stage were 6.8%, 20.3% and 4.9%, respectively under the impact of climate change (table 6).

The value of water requirement was rising at most of the phenological stages during the comparison period 2 compared with that during base period. Without consideration of phenophase change, there was significant increase in water requirement at every growing stage. The length of growing season during comparison period 2 was 7 days more than the growing season length during comparison period 1 (table 6).

3.4 Prediction on water requirement for spring wheat under climate warming

With the continuous development and maturity of the regional climate prediction model, many scholars have predicted the future climate change scenarios in China. In the National Assessment Report on Climate Change, the temperature was predicted under the four scenarios, GG, GS, A2, B2, in the 21st century, and the result showed that the average temperature over China would rise by ~ 1.1 – 2.1°C , by 2020 (Li *et al.* 2007). The warming trend in northwest China increased significantly and the tendency was ~ 4 – $6^\circ\text{C}/100\text{a}$, which was slightly higher than those of the global and China (Xu *et al.* 2003). On the foundation of previous research findings on change of crop phenological stage affected by temperature, this section was focused on analysing the impact of future warming on the crop phenophase and water requirement in the Heihe River basin.

Therefore, to predict phenological stage duration and water requirement of the crop under climate warming, this paper adapted firstly ATT method to determine each phenological stage duration, then analysed the change of phenological stage duration compared with those during base period that was the effect of climate warming on phenological stage duration. Afterwards, equations 2 and 3 were used to estimate the length of each

phenological stage and the quantity of water requirement with the consideration of climate warming.

3.4.1 Prediction on the change of spring wheat phenological stages

Using the results of previous researches on temperature prediction and response of crop phenological stage to climate change (Mu *et al.* 2014; Wang 2008; Rong *et al.* 2014), this study adopted the approach of ATT and numerical simulations to quantitatively analyse the change of crop phenological stages under climate change.

With the increasing temperature, the beginning date of each phenological stage had different degrees of advance, and the growing season length was shortened as a whole. Specifically, during the duration time from sowing to seedling, the beginning date increases linearly and the growth length decreased significantly along with the rise of temperature. The duration, time from seedling to tillering, from tillering to jointing and from jointing to heading, was approximately 18, 18, and 19 days, respectively, which were unchanged, basically. Although, the days during the period of heading to wax ripeness reduced significantly. Therefore, the temperature increased by 1°C on average, the beginning date of growth period was 2 days in advance and the growing season length was shortened by 2 days (table 7).

3.4.2 Prediction on the change of spring wheat water requirement

Under the context of climate warmth, crop water requirement in each phenological stage was obviously different (Liu *et al.* 2004; Wang *et al.* 2011; Li 2013; Wang 2014). With the increase of temperature, the amount of water requirement was decreased in the stage of sowing to seedling, while that in the stage of seedling–tillering was increasing, on average. Similarly, in both of the tillering–jointing stage and the jointing–heading stage, the amount of water requirement were

Table 7. *Change of phenological sages for spring wheat with increasing temperature in Heihe River basin. A represents the advanced days and L represents the length of phenological stage.*

Temperature		0	0.5	1	1.5	2	2.5	3	3.5	4
Stage										
Sowing–seedling	A	0	1	2	3	4	5	6	7	8
	L	24	25	25	23	22	20	19	18	18
Seedling–tillering	A	0	0	1	4	6	9	11	13	14
	L	18	17	15	17	18	19	19	19	18
Tillering–jointing	A	0	1	4	5	6	8	10	12	14
	L	17	20	20	19	18	17	17	18	18
Jointing–heading	A	0	–2	1	3	5	8	10	11	13
	L	19	19	19	19	19	20	19	18	17
Heading–wax ripeness	A	0	–2	1	3	5	7	10	12	15
	L	38	33	30	20	28	28	27	28	29
Growing season	A	0	3	9	12	15	17	21	22	24
	L	116	114	109	107	105	104	101	101	100

Table 8. *Change of spring wheat water requirement with increasing temperature in Heihe River basin. WR represents the value of water requirement and the unit is mm.*

Temperature		0	0.5	1	1.5	2	2.5	3	3.5	4
Stage										
Sowing–seedling		25.2	24.3	24.6	22.3	21.1	19.1	18	17	17
Seedling–tillering		39.7	38.5	34.5	38.7	41.2	42.5	42.4	41.9	39.5
Tillering–jointing		68.5	83.1	84.3	82.4	80	76.7	77.7	84	84.6
Jointing–heading	WR	112.5	97.9	117.2	119.9	122.2	131.3	127.3	123.4	120.3
Heading–wax ripeness		182.9	177.2	154.6	154.1	153.9	157.2	155.6	165.8	174.6
Growing season		428.9	421	415.2	417.4	418.5	426.8	421	432.1	436.1

increased gradually. The water requirement in the heading–wax ripeness stage was simulated to be reduced on average. During the growing season of spring wheat, the water requirement increased in general. According to the relation of temperature to water requirement, if the average temperature increased by 1°C, the water requirement during the growing season would be increased by 1.4 mm (table 8).

4. Conclusions

This study proposes a new approach of ATT method to analyse crop phenophase in regions where there is a lack of observational phenological data. And having been verified, the approach was applicable to divide the crop phenophase during the growing season in Heihe River basin as all of the errors were within the regulated criteria of error. Based on the above research results, we draw the main conclusions, including the following aspects.

Firstly, this study used the method of M–K test to define two periods, the base period without

climate change from 1961 to 1991, and the comparison period with climate change from 1992 to 2010. The comparison period of spring wheat consisted of the comparison period 1 with the change of crop phenophase, and the comparison period 2 without the change of crop phenophase. Next, this study analysed the variation of phenological stages, the growing length and water requirement for spring wheat under climate change. The results indicated that all of the beginning dates of phenological stages have been advanced to different extents, but the length of growing season was reduced by 7 days with climate change. During the crop growing season, the water requirement in the comparison period 1 was obviously reduced by 50 mm (11.5%) compared to the base period while water requirement in comparison period 2 was increased by 26.1 mm (6.0%) compared to the base period. We argued that the difference was partly due to the change of crop phenophase under the impact of climate change. Specifically, under the climate change, the water requirement at sowing–seedling stage, the seedling–tillering, the tillering–jointing, the jointing–heading and at the heading–wax ripeness stage were decreased by

17.4%, 8.4%, 6.8%, 20.3% and 4.9%, respectively, compared to the base period.

Based on the previous research on climate warming in the future, in this study, a numerical simulation was adopted to predict the change of phenophase and water requirement for spring wheat with rising temperature. We concluded that the temperature increased by 1°C on average, the beginning date of growth period was 2 days in advance, the growing season length was shortened by 2 days, and the water requirement increased by 1.4 mm during the growing season. These results provide reference both for improving irrigation scheduling and for the planning water requirement at the basin scale, especially where there were lack of phenological observations.

Also, there are limitations/assumptions in the study. Irrigation, inevitably, caused the dramatic change of soil moisture content, but this paper adopted the comprehensive approach of climatology to calculate crop water requirement without consideration of soil water conditions (under the circumstance of enough soil water). The evapotranspiration estimation model of the Penman–Monteith equation should be parameterised properly. In addition, this study only considered temperature change under the future scenario of climate change, which could lead to a greater uncertainty of the prediction on crop water requirement. And also, the results of crop water requirement were the average of the values of many years simulated by different climate change scenarios.

Acknowledgements

This work was supported by the State Key Development Program for Basic Research of China (Grant No. 2010CB951102), and the Foundation for Innovative Research Groups of the National Natural Science Foundation of China (Grant No. 51021066).

References

- Allen R G, Pereira L S and Dirck R 1998 Crop evapotranspiration guidelines for computing crop water requirements.
- Feng L Y, Zhang L Y and Guang W W 2009 Impacts of climate change on irrigation water requirements of rice: A case study of Gaoyou Irrigation District; *Eng. J. Wuhan University* **42** 609–613.
- Feng Z, Fang W B and Lin C L 2004 A method to extract regional crop growth profile with time series of NDVI data; *J. Remote Sens.* **8** 515–528.
- IPCC (Climate Change) 2007 The Physical Science; Cambridge Press, New York.
- Jia J Y and Gao J P 2009 Studies on climatic resources change for Maize over last 46 years in northeast China; *Chinese J. Agro-Meteorol.* **30** 302–307.
- Juan L Z, Guang Y X and Feng W W 2009 Characteristics of agricultural climate resources in three provinces of northeast China under global climate change; *Chinese J. Appl. Ecol.* **20** 2199–2206.
- Li J H, Yang X G and Cao S Y 2009 Water requirement and crop coefficient of different planting patterns in the Zhangye area of Gansu Province; *Acta Agricultural Jiangxi* **21** 17–20.
- Li X Y, Qin D H and Li J Y 2007 *National assessment report on climate change*; China Meteorological Press, Beijing.
- Li Z G, Yang P and Tang H J 2011 Trend analysis of typical phenophases of major crops under climate change in the three provinces of northeast China; *Scientia Agricultural Sinica* **44** 4180–4189.
- Li S 2013 *The impact of climate change on the agricultural irrigation water requirement in the northwest arid region, China*; Hebei, Hebei Normal University.
- Liu X Y and Lin E D 2004 Impact of climate change on water requirement of main crops in north China; *J. Hydraul. Eng.* **2** 77–87.
- Lu Q Y and Wang L 1965 The accumulated temperature of the growth period on rice, wheat and cotton in China; *ACTA Agronomical Sinica* **4** 157–170.
- Mei S M, Xia J L and Huan Y R 1998 Effect of climatic factors on spike grain number in winter wheat; *Chinese J. Agro-Meteorol.* **19** 8–12.
- McVicar T R, Roderick M L and Donohue R J 2012 Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation; *J. Hydrol.* **416** 182–205.
- Mu J, Zhao J F and Guo J P 2014 Response of spring Maize growth stage to climate change in northeast China over the past 30 years; *J. Appl. Meteorol. Sci.* **25**(6) 680–689.
- Nelson G C, Rosegrant M W and Koo J 2009 *Climate change: Impact on agriculture and costs of adaptation*; Washington DC: International Food Policy Research Institute, pp. 2–14.
- General Office of the State Council of the People (GCSCP) 2008 *China's policies and actions for addressing climate change*; White papers of the Chinese government.
- Ping Z J, Yi W C and Guang Y X 2009 Impact forecast of future climate change on maize water requirement in three provinces of northeast China; *Trans. Chinese Soc. Agr. Eng.* **25** 50–55.
- Penman H L 1948 Natural evaporation from open water, bare soil and grass; *Proc. Roy. Soc. London A* **193** 120–146.
- Qing M S, Qi W, Ping G J and Sheng S Z 2007 Geographical change law of effects of corn plastic mulching on increasing temperature and production in northeast China; *Trans. Chinese Soc. Agr. Eng.* **23** 67–71.
- Rosenzweig C and Ping M L 1994 Potential impact of climate change on world food supply; *Nature* **367** 133–138.
- Rong Y L, Zhang X, Ma Z F, Shao C, Yang H Y and Bao J L 2014 Analysis of climate features and impacts upon agriculture in Songjiang in recent 55 years; *Atmos. Sci. Res. Appl.* **2** 43–54.
- Sheng Y, Peng P and Cavadias G 2002 Power of the Mann–Kendall and Spearman's rho tests for detecting and monotonic trends in hydrological series; *J. Hydrol.* **259** 254–271.
- Todico F and Vergni L 2007 Climatic change in central Italy and their potential effects on corn water consumption; *Agr. Forest Meteorol.* **8**.
- Wang Z F, Yang L X, Xiao Bai and He C S 2015 Evaporation paradox in the Heihe River basin; *J. Glaciol. Geocryol.* **37** 1323–1332.

- Wang W G, Shao Q X and Peng S Z 2012 Reference evapotranspiration change and the causes across the Yellow River basin during 1957–2008 and their spatial and temporal differences; *Water Resour. Res.* **48**(5) W05530.
- Wang X J 2014 *The response of crop water requirement to climate change in the arid-region of northwest China*; Northwest A & F University.
- Wang H L, Wang R Y, Zhang Q, Niu J Y and Lv X D 2011 Impact of warming climate on crop water requirement in Gansu Province; *Chinese J. Eco-Agriculture* **19**(4) 866–871.
- Wang Y P 2008 *The impacts of climate change on surface dry-wet status and growing season from 1960 to 2005 in three provinces of northeast China*; Nanjing Agricultural University, Nanjing.
- Xiang G S, Ming H D and Hua L Y 2008 Agriculture irrigation water requirements change and R/S analysis of Jinshajiang dry-arid valley in recent 40 years; *Advan. Water Sci.* **19** 352–360.
- Xiao G J, Qiang Z and Jin W 2007 Impact of global climate change on agro-ecosystem: A review; *Chinese J. Appl. Ecol.* **18** 1877–1885.
- Xu Y, Ding Y H and Zhao Z C 2003 A scenario of season climate change of the 21st century in northwest China; *Climatica Environ. Res.* **18** 19–25.
- Yan D H, Geng S M and Luo X X 2011 Temporal and spatial evolution of season climate in northern China; *Scientia Geographica Sinica* **9** 1105–1110.
- Yin H X, Zhang B, Wang Y M, Zhang Y N, Wang Q and Zhao Y F 2012 Research on the change trend of crop water requirement in the middle of Heihe River basin in the recent 43 years; *Resour. Sci.* **34**(3) 409–417.
- Yang Y M, Feng Z D and Zhou J 2008 Evaporation in Heihe River basin based on SEBS model; *J. Lanzhou Univ. (Natural Sci.)* **44** 1–6.

MS received 19 June 2016; revised 22 September 2016; accepted 25 September 2016

Corresponding editor: SUBIMAL GHOSH