Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2018.22557

121 (2018) 357–364
July

Characteristics of agricultural climate factors during persistent droughts in North China

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Received 26 February 2018; Accepted 28 May 2018

ABSTRACT

The spatio-temporal evolvements of effective rainfall, active accumulated temperature, and sunshine hours during drought periods in the North China were analyzed by using the methods of standardized precipitation index (SPI), Mann-Kendall (M-K), and ArcGIS, based on the daily climatic data of 93 meteorological stations from 1961 to 2010. The results were as follows: (1) The effective rainfall between the drought period in spring and summer and the multiyear showed no obvious differences, while it in crop growth period was less than the multiyear average, with the difference of 30 mm. The active accumulated temperature (≥0°C) also displayed no difference, while in crop growth period it showed obvious differences, with the value as 70°C and the maximum value up to 90°C. The same rules were shown in the active accumulated temperature (≥0°C) and in the active accumulated temperature (≥10°C). Sunshine hours in drought periods showed less changes than average value in spring, summer, and growth period. (2) In the north-eastern Inner Mongolia, the effective rainfall in drought period in spring leveled with the average value. The difference of active accumulated temperature (≥0°C) between spring, summer, in crop growth period, and multiyear reached 70°C, 90°C, and 50°C, respectively. The active accumulated temperature (≥10°C) showed the same rule with the active accumulated temperature (≥0°C); In the central and northern Shanxi, the effective rainfall in drought period in spring and summer displayed less difference with the average value, while the difference in crop growth period was the most with the value of 65 mm; In Hebe, Beijing, and Tianjin, the variation of effective rainfall was not apparent in spring and summer, but there was a difference of 65 mm in the crop planting area. The active accumulated temperature (≥0°C) in drought period in spring was higher than the average temperature for many years with the difference of 70°C and in summer with the difference of 90°C in the most severely affected areas.

Keywords: Drought period; Effective rainfall; Active accumulated temperature; Sunshine hours; North China

1. Introduction

In recent years, droughts have been occurring frequently, and their impacts on the ecosystems [1,2], agriculture, and economic and social sectors [3–5] were being aggravated by the rise in water demand and the variability in hydro-meteorological variables due to the growth in population and expansion of agricultural and industrial sectors, and partly because of climate change and contamination of water supplies [6]. Drought as the most important limiting factor for agriculture could lead to reduced water supply and crop failure. In China, agriculture played a central role in ensuring food

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Presented at the 3rd International Conference on Recent Advancements in Chemical, Environmental and Energy Engineering, 15–16 February, Chennai, India, 2018.

security and welfare of 1.3 billion people [7]. North China was the most important food basket of China, where the majority of wheat and corn were produced [8]. Since the 1980s, there were nationwide and most serious drought-hit areas in North China. The total areas of arable land in North China were 3,630.2 × 10^4 km^2, and its grain output were 130 million tons per year. In recent years, under the combined effects of climate change and human activities, the drought frequency showed an increasing trend in North China. Therefore, the characteristics of the agro-climatic factors during the drought periods need to be analyzed in order to provide information for agricultural production in North China.

The causes of droughts in North China were complex. Summer 200 hpa vector wind anomaly field and 850 hpa field leaded to the drought-prone in North China. It was found that the intensity and the central position of the South Asia high could affect the droughts and floods. The droughts in summer were the consequence of persistent anomalous circulation over the Eurasia. Drought strength enhanced, and the spatial distribution of rainfall showed the regional consistent pattern. Furthermore, there was less difference of the rainfall between less rainfall years and normal rainfall year, whereas there was more difference between more rainfall year and normal rainfall year. Therefore, droughts were of great importance in water resources planning and management and need to be received much attention. But as the important grain production region, there were less studies on the characteristics of agricultural climate factors in drought periods in North China.

In the study, we used the Mann-Kendall (M-K) method and the drought index of monthly-scale standardized precipitation index (SPI) to analyze the temporal variability of climatic factors of effective rainfall, active accumulated temperature, and sunshine hours, and studied the spatial variation of agricultural climatic factors with the help of geographic information system technology in crop growth periods in droughts in North China, in order to provide the theoretical support for the agricultural and economic development in North China.

2. Study area and method

2.1. Study area

North China was located between 34.58°N–47.65°N and 103.36°E–123.71°E in China. It occupied an area of 151.58 × 10^4 km^2 and consisted of five provinces including Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia (Fig. 1), which was one of the most important wheat production regions in China. The main crops were wheat, rice, corn, sorghum, millet, and sweet potatoes. This region was in a semi-humid and semi-arid environment and was strongly affected by human activities and climatic changes. Generally, the south area of Huaihe River was the northern subtropical humid climate, while north of Huaihe River belonged to the warm-temperate humid or sub-humid climate zone. It was dry and cold in winter, while was high temperature and rainy in summer. Drought occurred with little rain in spring. Evaporation was strong in North China. The values of annual effective precipitation, annual relative humidity, wind speed, vapor pressure, and annual sunshine hours were 358 mm, 53.6%, 2.9 m×s^{-1}, 7.1 hPa, and 1,581 h, respectively.

2.2. Data and methods

The study used the data of 95 meteorological stations of the daily rainfall, temperature, and sunshine time data from 1961 and 2010 in North China to analyze the characteristics of agricultural climatic factors. Especially considering the concentrated rainfall from March to September in North China, the critical periods of winter wheat planting and growth were selected from March to September as the agricultural growing season. The methods of SPI, the M-K and inverse distance weighting (IDW) were used in this article.

The active accumulated temperature referred to the cumulative value of the temperature greater than or equal to the biological limit temperature in a certain time. The accumulated temperature ≥0°C (or ≥10°C) was the sum of the daily average temperature greater than or equal to 0°C (or 10°C) in a year. The method of IDW was used to solve the uneven spatial distribution and sparse of the stations in large scale.

The SPI [9] was widely used to define meteorological droughts [10–13] and has proved to be a useful tool in the estimation of the intensity and duration of drought throughout the world in both research and operational modes because it was normalized to a location and was normalized in time. It determined the rarity of a current drought event, as well as the probability of the precipitation necessary to end the current drought. The index standard of the SPI is shown in Table 1.

Using the method of M-K, the trends of effective rainfall, active accumulated temperature, and sunshine hours were tested. When $Zc > 1.96$ or $Zc < -1.96$, the trend was clear and passed the test confidence level of 0.95. If $\beta = 0$, the original hypothesis was rejected; if $\beta > 0$, the trend was rising; and if $\beta < 0$, the trend was downward.

Effective rainfall referred to the rainfall less than surface runoff and crop water demand. Generally effective precipitation could be calculated according to experienced effective utilization coefficient:

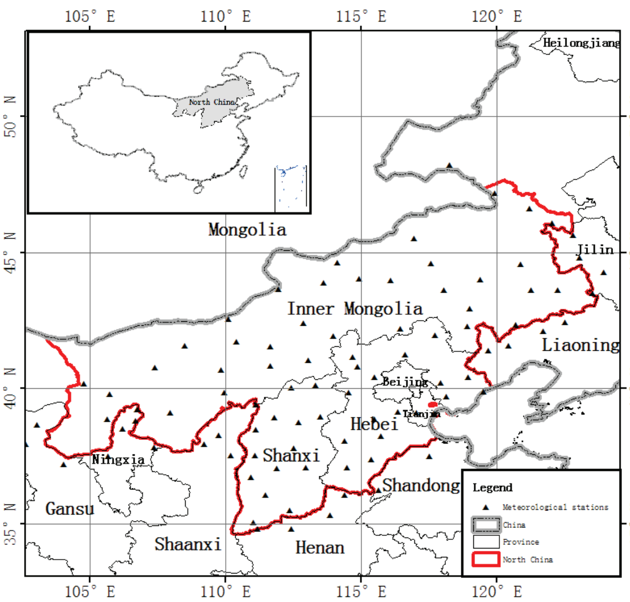

Fig. 1. Location of the meteorological stations used in this study in North China.

$$P_\theta = \alpha P \tag{1}$$

where P_θ was effective rainfall (mm), P was the rainfall (mm), and α was experienced effective utilization coefficient for rainfall. If $P < 50$ mm, $\alpha = 1.0$; if $50 \leq P < 150$ mm, $\alpha = 0.8–0.75$; and if $P \geq 150$, $\alpha = 0.7$. According to the experienced effective rainfall utilization coefficient, effective rainfall could be calculated.

3. Results

3.1. Temporal and spatial variation of the drought in North China

The monthly scale SPI was calculated during 1961–2010. A remarkable characteristic was summarized that there was an increasing drought frequency presented in recent 20 years—showing 41 times during 1961–1970, 33 times during 1971–1980, 29 times during 1981–1990, 45 times during 1991–2000, and 42 times during 2001–2010. During the periods of the end of 1965 to the end of 1968, the summer of 1980 to the summer of 1984, the end of 1998 to the beginning of 2003, and the end of 2005 to the begin of 2007, there was a prolonged drought in North China. The climate disasters caused by the superposition effects of interannual drought were very serious. North China was dominated by the light and medium drought, with less heavy or severe drought. The percentages of the drought times for the light drought, medium drought, heavy drought, and severe drought to the total drought times from 1961 to 2010 were 47%, 33%, 16%, and 4%, respectively.

In this paper, the typical drought years of 1962, 1965, 1968, 1972, 1980, 1982, 1989, 1997, 1999, 2000, 2001, 2002, 2005, 2006, 2007, and 2009 were chosen by the SPI value below –0.5. The paper used the differences of agroclimatic factors between the values in certain drought spells and their multiyear average values to discuss the variation characteristics of effective precipitation, active accumulated temperature, and total sunshine hours during drought period.

The spatial distribution of drought frequency during the past 50 years showed that drought times in the middle of North China exceeded 200, exceeded 100 in the north eastern parts except some individual stations above 200 and exceeded 150 in the western parts, as shown in Fig. 2. The continuous drought had a severe influence to the main crops of wheat, corn, and beans. Continuous droughts led to abnormal growth or even death to plants, and finally led to a production drop and degradation in quality. So it was necessary to know the characteristics of agroclimatic factors in drought periods in order to provide the information to cope with drought. According to the spatial distribution of drought frequency in different regions, North China was divided into three parts in this paper—northeast region (40°N–47°N and 117°E–125°E), western region (37°N–50°N and 105°E–120°E), and middle regions.

Table 1
The drought classification of standardized precipitation index (SPI)

Grade	Drought grades	SPI value
1	No drought	$–0.5 < \text{SPI}$
2	Light drought	$–1.0 < \text{SPI} \leq –0.5$
3	Medium drought	$–1.5 < \text{SPI} \leq –1.0$
4	Heavy drought	$–2.0 < \text{SPI} \leq –1.5$
5	Special drought	$\text{SPI} \leq –2.0$

3.2. Temporal and spatial variation of effective rainfall in drought period

The average value of effective rainfall was 246 mm during crop growth period for the past 50 years. The effective rainfall in drought period was below to the average values of 246 mm, and the rainfall disparity increased with the drought intensity. Furthermore, the rainfall varied regularly in drought period with the increasing during 1961–1980, decreasing during 1980–1997, and rising during 1997–2010. The tendency degree of 0.217 mm/a and Zc of 8.4 were obtained from the M-K result, indicating that effective rainfall decreased by 0.217 mm/a and the decreasing tendency passed the test with 5% significance level during the drought period.

The disparities of spatial variations of the effective rainfall in spring, summer, and growth period in drought period and the multiyear average value are shown respectively in Fig. 3. The results showed that the disparity was not so significant in spring with merely 11 mm, which related to the less rainfall in spring but more in summer. The disparity was also insignificant in summer, and it was positive in most areas except north eastern Inner Mongolia, south western Shanxi, southern and northern Hebei with a disparity of about –10 mm. The downward had a significant influence on the beans growth in Inner Mongolia and Shanxi and the corn in Hebei.

The tendency was insignificant in the north eastern and western regions, while it was significant in the middle part in

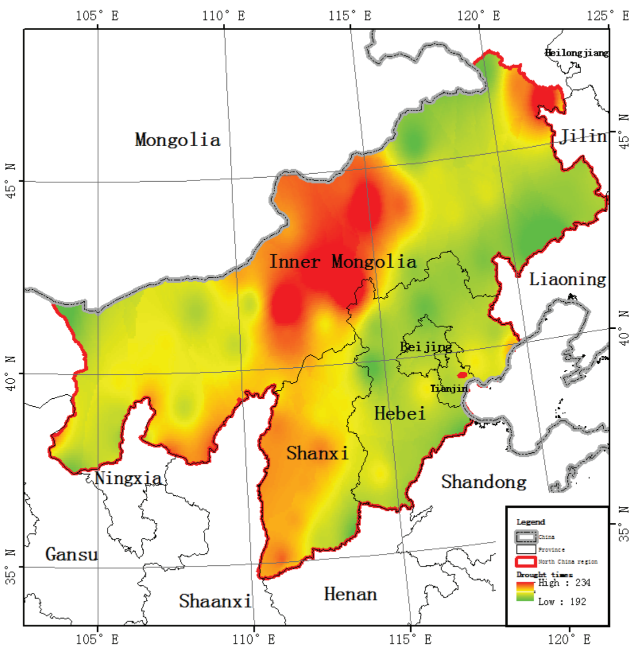

Fig. 2. Spatial distribution of drought times during the past 50 years in North China.

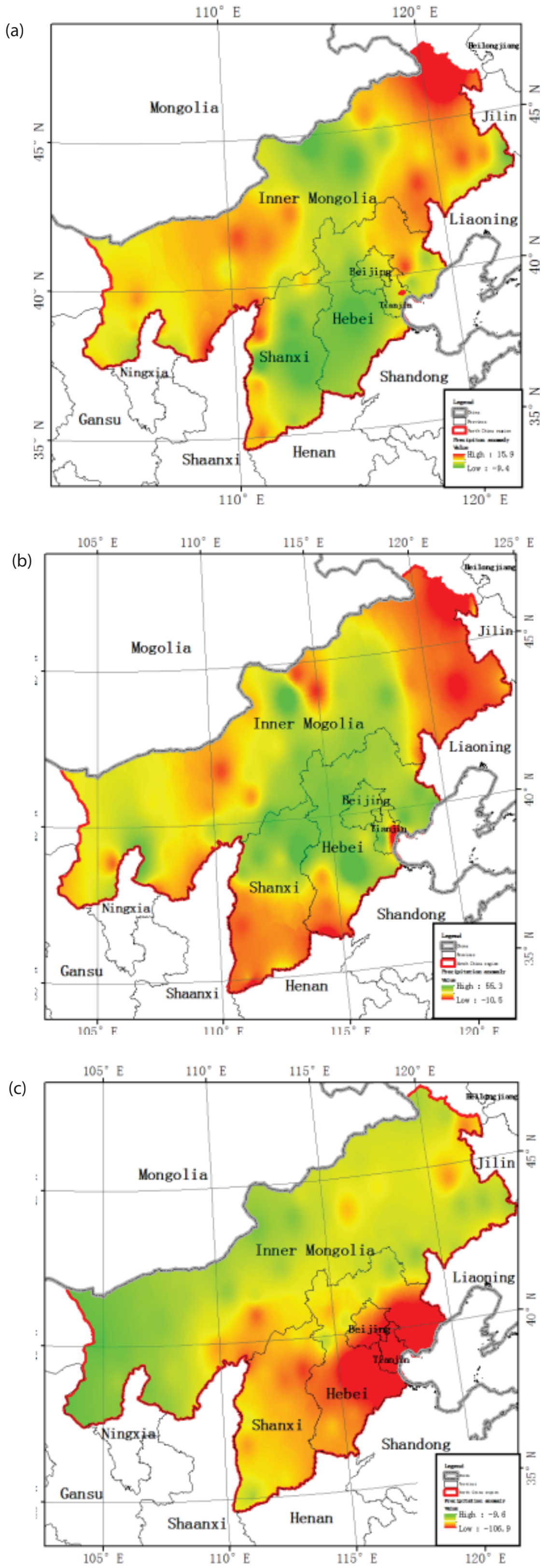

Fig. 3. The spatial distribution of the difference of effective rainfall between the multiyear average value and the value in drought periods in (a) spring, (b) summer, and (c) crop growth period.

the crop growth period. The influence degree was relatively low with a disparity of 17 mm in the western Inner Mongolia, while the influence degree was more remarkably with a disparity of –30 mm or even –50 mm in some meteorological stations in the north eastern and middle regions. The influence was heavy in Shanxi, Hebei, Beijing, and Tianjin with a disparity of 65 mm, except some meteorological stations in Hebei with a disparity of 30 mm and a disparity exceeding 75 mm at the junction of Hebei and Beijing. The decreasing rainfall in drought periods limited the water supply for winter wheat, leading to a relatively large influence on the growth of winter wheat.

3.3. Temporal and spatial variation of active accumulated temperature in drought period

The active accumulated temperature ≥0°C represented the quantity of heat during the agricultural growth period. When the average daily temperature exceeded 0°Cin spring, snow began to melt and people began to inseminate frigostable plants such as wheat. The multiyear average value of active accumulated temperature (≥0°C) was 31,890°C during crop growth period in North China. The active accumulated temperature increased continuously during 1997–2001 and decreased after the year of 2001. In the recent 50 years, the active accumulated temperature (≥0°C) represented an increasing tendency mostly and the tendency degree was 23.4°C/a obtained by M-K method, which indicated that the active accumulated temperature (≥0°C) during the dry spell had a relative large increasing amplitude of 23.4°Cby year. Effective rainfall before 1989 followed the same law of active accumulated temperature (≥0°C) and represented the same negative anomaly (less precipitation and lower temperature). But after 1989, the active accumulated temperature (≥0°C) represented positive anomaly in the opposition to negative anomaly of the effective rainfall, which meant less precipitation and higher temperature. Thus, it was obvious that the causes of droughts in about 1989 were different.

The active accumulated temperature (≥10°C) was a key index to study the characteristics of climatic factors in the crop growth period in spring. When the daily average temperature exceeded 10°C, crops for spring ploughing began to seed and grow, then most plants came into their bloom periods. The active accumulated temperature (≥10°C) followed similar law of active accumulated temperature (≥0°C) except the years of 1965, 1989, and 2006. For example, the active accumulated temperature (≥10°C) in 2006 was higher than the value in 2005, while the active accumulated temperature (≥0°C) was lower than that in 2005. The tendency degree was 32.1°C/a obtained from M-K result, which indicated that the active accumulated temperature (≥10°C) during dry spell had a relative increase amplitude of 32.1°C/a.

The spatial characteristics of the differences of active accumulated temperature (≥0°C) were studied between the multiyear average value and the value in spring, summer, and the crop growth period, as shown in Fig. 4. The results indicated that the difference of active accumulated temperature (≥0°C) between the multiyear average value and the average value in spring was less than 5°C in the middle and western Inner Mongolia and in the most regions of Shaanxi— the spring plants growing regions, while the disparity was as more as

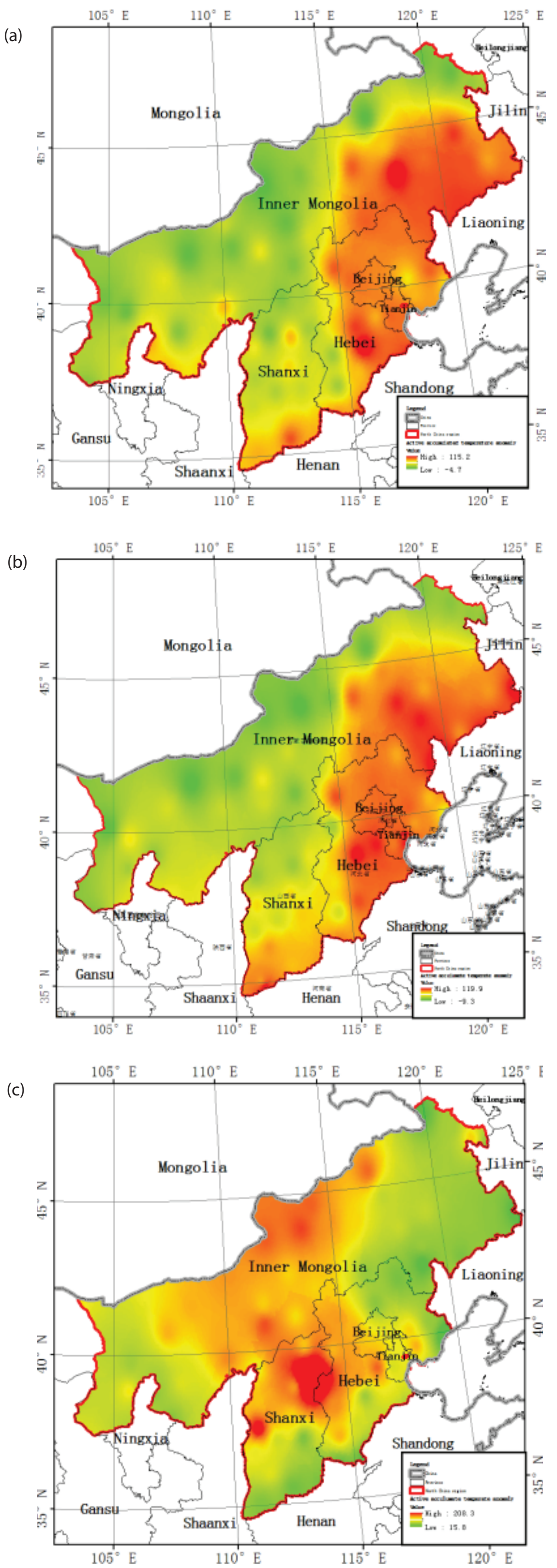

Fig. 4. The spatial distribution of the difference of active accumulated temperature (≥0°C) between the multiyear average value and the value in drought periods in (a) spring, (b) summer, and (c) crop growth period.

70°C in the north-eastern Inner Mongolia, Hebei, Beijing, and Tianjin. The variation of accumulated temperature had different effects on the growth of wheat, corn, potato, and durra in Inner Mongolia, and core, bean, potato, and cotton in Hebei, Beijing, and Tianjin. The difference of active accumulated temperature (≥0°C) between the multiyear average value and the average value in summer followed the similar law in spring, with the value of the difference reaching as 90°C in north-eastern Inner Mongolia, southern Shanxi, Hebei, Beijing, and Tianjin. The spatial difference in summer influenced the corn growth in Beijing, Tianjin, and Hebei and the bean in Inner Mongolia.

The active accumulated temperature (≥0°C) varied obviously during the crop growth period in dry spell in most parts of North China except in the north-eastern and middle parts. The disparity of active accumulated temperature (≥0°C) was about 50°C in the eastern and western Inner Mongolia. The disparity of active accumulated temperature (≥0°C) was about 70°C in the middle of Inner Mongolia and even above 90°C in some meteorological stations. The disparity of active accumulated temperature (≥0°C) achieved the maximum value of 207°C in the middle and northern parts of Shaanxi, especially at the junction of Shaanxi and Hebei. In Beijing and Tianjin, the average value of the disparity was 101°C, showing obvious impacts on the crops. Moreover, the droughts occurred so frequently in the middle Shanxi that seriously affected the crop growth and development for winter wheat.

The spatial distributions of active accumulated temperature ≥0°C and ≥10°C were similar (Fig. 5). The disparity of active accumulated temperature (≥10°C) in spring and summer both was as less as 7°C in the middle and western Inner Mongolia and in the most parts of Shanxi, while more than 85°C in Hebei, Beijing, Tianjin, and north eastern Inner Mongolia. During the crop growth periods between March and September, the active accumulated temperature (≥10°C) was higher than the multiyear average value. The disparity was relatively less in the eastern and western parts, with the value as above 141°C. The disparity of active accumulated temperature (≥10°C) was about 207°C in the middle Inner Mongolia, with the most value occurring in the border between Shanxi and Hebei.

3.4. Temporal and spatial variation of sunshine hours in drought period

Sunshine was the most important climatic factor characterized by climate change. The results showed that the multiyear value of total sunshine hours reached 2,824.1 h in droughts before 2002 in North China. Moreover, the annual value of sunshine hours in droughts was more than the multiyear average value. Since 1965, total sunshine hours showed a decreasing trend in drought years. According to the M-K test, the linear tendency of the sunshine hour was –20.1 h/a, which indicated that annual sunshine hours reduced by a big margin in droughts in North China.

The spatial distribution of the difference of sunshine hours between the multiyear average value and the value in drought periods in spring, in summer and in the crop growth period is shown in Fig. 6. The results showed that there were no differences between the multiyearly average value and the

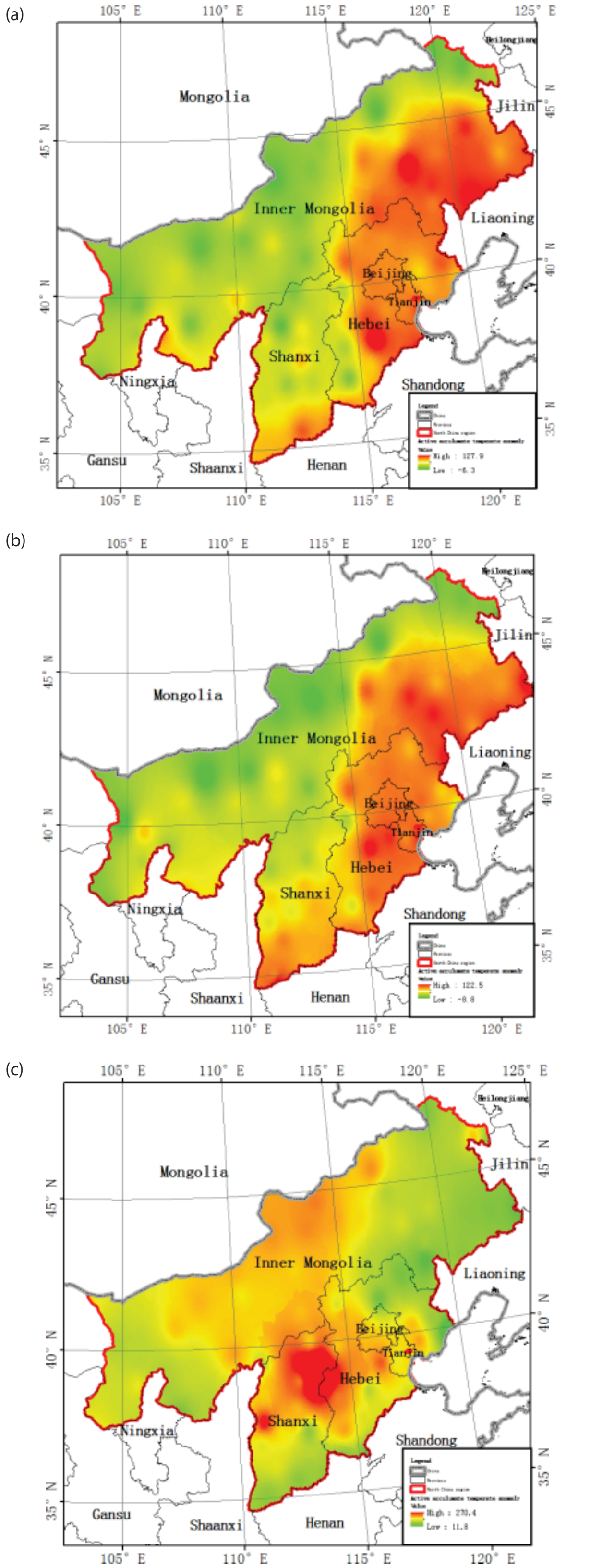

Fig. 5. The spatial distribution of the difference of active accumulated temperature (≥10°C) between the multiyear average value and the value in drought periods in (a) spring, (b) summer, and (c) crop growth period.

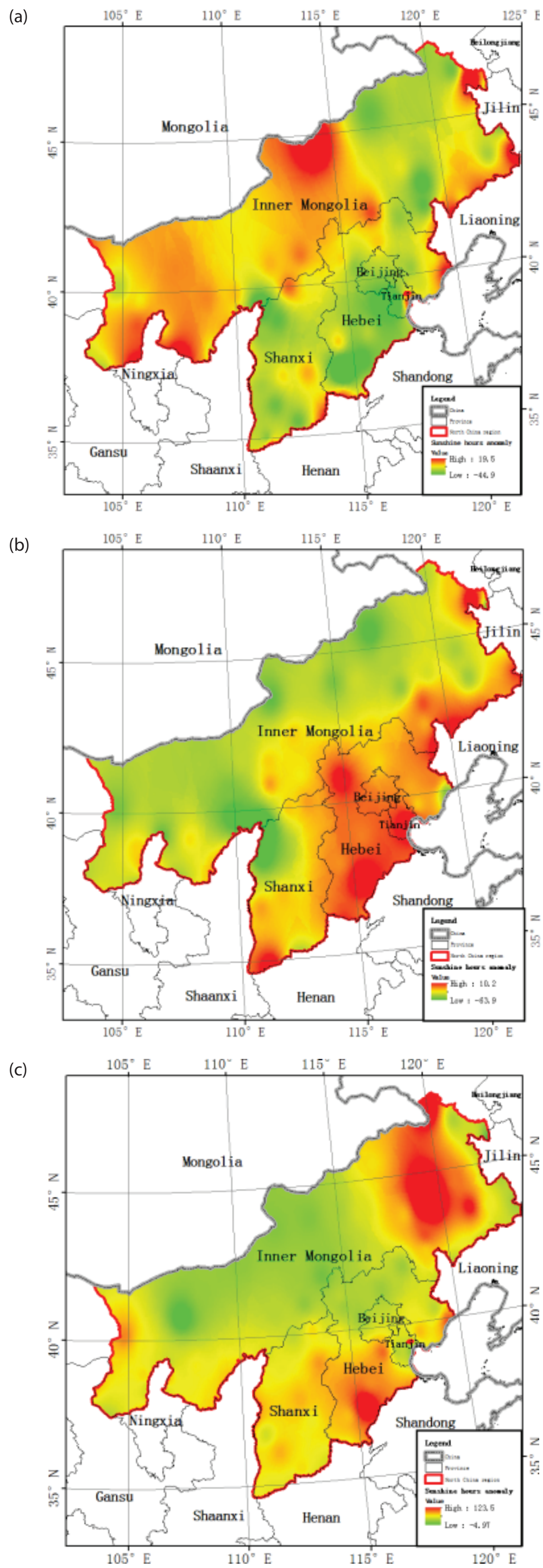

Fig. 6. The spatial distribution of the difference of sunshine hours between the multiyear average value and the value in drought periods in (a) spring, (b) summer, and (c) crop growth period.

value in drought periods in spring. The difference between most of the Inner Mongolia region and central region of Shaanxi was 7 h, while it was negative in Hebei, Beijing, and Tianjin. The difference in the centre of Inner Mongolia was less than the average, with the value of –4.0 h, while the differences of Shanxi, Hebei, Beijing, and Tianjin were more than the average, with the average as 9 h in droughts. The sunshine hours had a relatively wide influence scope during growth period in North China. The difference of sunshine hours between the multiyear average value and the value in drought periods in the crop growth period showed that the difference was more than 55 h in the northeast of Inner Mongolia, which was the worst affected areas, while the difference was the least as 15 h in the centre of Inner Mongolia. The difference was 30 h in Shaanxi, Hebei, and Beijing. The winter wheat was immediately affected in Shaanxi, Hebei, Beijing, and Tianjin.

In Inner Mongolia, for the north-eastern Inner Mongolia, the effective rainfall in drought period in spring leveled with the average value, and it was less than the average by 10 mm in the drought period in summer. The difference of active accumulated temperature (≥0°C) between in spring, summer, in crop growth period, and multiyear reached 70°C, 90°C, and 50°C, respectively in the northeast of Inner Mongolia. The active accumulated temperature (≥10°C) showed the same rule with the active accumulated temperature (≥0°C). The difference of sunshine hours in drought period between in spring and multiyear was 7 h, while there was no obvious change in summer and the most difference in the crop growth period with the value of 55 h. In the northeast of Inner Mongolia, the spring wheat, corn, and potato were greatly influenced by the active accumulated temperature. The impact of climatic factors on summer sowing beans was relatively small while winter wheat was greatly affected by active accumulated temperature and total sunshine hours. In Inner Mongolia, the west of Inner Mongolia was the least affected region. Effective rainfall in spring and summer showed no change and the difference value of crop growth period was 17 mm. The difference value of active accumulated temperature (≥0°C) in spring, summer, and crop growth period was about 7°C and there was no obvious variation for sunshine hours.

In Shanxi, the central and northern regions were frequently affected by droughts. The effective rainfall in drought period in spring and summer displayed less difference with the average value, while the difference in crop growth period was the most with the value of 65 mm. In the central and northern Shanxi, especially in the junction of Shanxi and the central Hebei, the difference of active accumulated temperature (≥0°C) in crop growth period reached 207°C. The sunshine hours in spring experienced less variation and the difference in summer and in crop growth period were only 9 and 55 h, respectively. In the central and northern of Shaanxi, the climatic factors showed less variation in spring and summer, exerting little effect on the sowing of corn, soybean, and potato. However, the impact in crop growth period was relatively severe, posing more influences on the growth of winter wheat.

Hebe, Beijing, and Tianjin were frequently hit by the droughts. The variation of effective rainfall was not apparent in spring and summer, but there was a difference of 65 mm in the crop planting area and 75 mm at the junction of Hebei and Beijing. The active accumulated temperature (≥0°C) in drought period in spring was higher than the average temperature for many years with the difference of 70°Cand in summer with the difference of 90°C in the most severely affected areas. The average difference in crop growth period in Beijing and Tianjin was 101°C and Beijing and Tianjin were the most affected regions. The difference of average sunshine hours in crop growth period was around 30 h and the value exceeded 80 h in some regions. The agriculture were severely affected by the droughts in the northern regions and the impacts of climate variation on the growth of winter wheat, corn, cotton, soybeans, and potato greatly required special attention.

4. Discussions

This study aimed at the temporal and spatial analysis of the variation characteristics of agricultural climatic factors in drought periods in North China. Only rainfall data were used for the calculation of the drought based on the SPI index, thus the drought identification was limited. Discussions were as follows according to the above preliminary results:

(1) The rainfall of drought years in northern regions had some periodical features. The effective rainfall in drought periods increased from 1961 to 1989, while it decreased significantly by 0.217 mm/a with Zc less than –1.96 from 1997 to 2010. The trend of effective rainfall was related to the rainfall periodicity in North China. The periodic variation of rainfalls in drought years in North China was bound up with the low frequency oscillation of 2–5 A and the long periodic oscillation of 10–20 A. In recent years, the average annual rainfall reduced by 2 mm per year in North China, and the total reduction was 95 mm. The conclusion of this study was in accordance with the overall variation tendency of the rainfall. Therefore, how to deal with the impact of spatial-temporal variation of precipitation in droughts in North China on agricultural water demand was the focus of future work.

(2) The accumulated temperatures in drought periods showed an upward trend generally. On the spatial scale, accumulated temperatures in the upper and middle regions changed less, while other regions increased dramatically. The tendency of active accumulated temperature was affected by the climate change in North China. An overall warming trend of the average temperature in North China resulted in the increase for active accumulated temperature. The upward tendency of temperature in recent years was evident in the northern China, including North China, northeastern and northwestern China.

(3) The average sunshine hours in drought periods in North China were 2,824.1 h. Annual sunshine hours in drought years were constantly greater than the average value before 2002, while less than the mean value after the year of 2002. Total sunshine hours in drought years showed a declining tendency and it reduced greatly with an annual rate of 20 h. The reason was that increased rainfall leads to reduced sunny days and the decrease of sunshine duration. Another cause was the increase of atmospheric aerosol caused by the expansion of smoke and dust, particles and grains, etc. in the last few years, reducing the duration of sunshine.

5. Conclusions

From the temporal scale, the effective rainfall and sunshine hours decreased generally, while active accumulated temperature showed an increasing trend in drought periods in North China. The effective rainfall between the drought period in spring and summer and the multiyear showed no obvious differences, while the effective rainfall in droughts in crop growth period was less than the multiyear average, with the difference of 30 mm, and the maximum value up to 50 mm. The active accumulated temperature (≥0°C) between the drought period in spring and summer and multiyear displayed no difference, while the active accumulated temperature (≥0°C) between the drought period in crop growth period and the multiyear showed obvious differences, with the value as 70°C and the maximum value up to 90°C. The same rules were shown in the active accumulated temperature (≥0°C) and in the active accumulated temperature (≥10°C). Total sunshine hours in drought periods showed less changes in spring, summer, and growth period. Effective rainfall and active accumulated temperature changed more in crop growth period, indicating that the effective rainfall and active accumulated temperature impact on winter wheat growth in drought periods.

From the spatial scale, the difference of effective rainfall was not obvious generally. The effective rainfall in the western and north-eastern areas in drought periods was almost the same as the average value, while there was a small reduce in the centre of North China. The effective rainfall in drought periods in summer changed much more than the average value in the northeast of North China, in the central of Shanxi and Hebei region, while the others did not change significantly. The effective rainfall in drought periods in crop growth period in the west of North China changed the least, while the most in the centre, the northeast followed by. The rules were the same about effective rainfall and active accumulated temperature for the affected areas. The difference of active accumulated temperature between in the drought periods and in the multiyear was obvious in the western and central Shanxi, and the north-eastern and central of Hebei, Beijing, and Tianjin. The sunshine hours changed more in the centre of North China and less in the north-eastern regions.

Acknowledgments

The authors acknowledge the planning project of philosophy and social science in Tianjin (Grant no: TJGL16-019), the Open Research Fund of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research (Grant no: IWHR-SKL-201503), the planning project of philosophy and Social Sciences in Tianjin (Grant no: TJLJ15-008), and the School Green Development Research Fund Project of the Ministry of Education (Grant no: LSFZ1601).

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