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Research Article

Spatiotemporal Variation and Abrupt Change Analysis of Temperature from 1960 to 2012 in the Huang-Huai-Hai Plain, China

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Based on a monthly dataset of temperature time series (1960–2012) in the Huang-Huai-Hai Plain of China (HHHPC), spatiotemporal variation and abrupt change analysis of temperature were examined by moving average, linear regression, spline interpolation, Mann-Kendall test, and moving *t*-test. Major conclusions were listed as follows. (1) Annual and seasonal temperature increased with different rates on the process of fluctuating changes during 1960~2012. The upward trend was $0.22^{\circ}C\ 10a^{-1}$ for annual temperature, while it was very significant in winter ($0.34^{\circ}C\ 10a^{-1}$) and spring ($0.31^{\circ}C\ 10a^{-1}$), moderately significant in autumn ($0.21^{\circ}C\ 10a^{-1}$), and nonsignificant in summer ($0.05^{\circ}C\ 10a^{-1}$). (2) The spatial changes of annual and seasonal temperature were similar. The temperature increased significantly in Beijing and its adjacent regions, while it was nonsignificant in the central and southern regions. (3) The spring, autumn, winter, and annual temperature had warm abrupt change. The abrupt change time for winter temperature was in the late 1970s, while it was in the late 1980s and early 1990s for spring, autumn, and annual temperature. (4) Macroscopic effects of global and regional climate warming and human activities were probably responsible for the temperature changes. The climate warming would influence the hydrological cycle and agricultural crops in the study area.

1. Introduction

Climate change is a global issue, which is greatly concerned by the international community [1]. Many studies were conducted on the climate change and forecasted its possible trends and influences in the past and the present [2]. Temperature is one of the most important variables for diagnosing climate change. Temporal and spatial variation of temperature plays a great role in the ecological environment changes and economic development [3, 4] and directly or indirectly influences all kinds of the natural and biological system in many places [5]. Recent studies further implicated that temperature change had some irreversible impacts on the regional hydrological cycles [6] and agricultural activities [7, 8]. Therefore, under the background of global warming, temporal and spatial variation of temperature has achieved great attention by many scientists.

The Huang-Huai-Hai Plain of China (HHHPC) is an important region of agricultural production [9] and plays a great role in the sustainable development of economy and ecology. Due to its important geographical location, it is very vulnerable to climate change. In particular, frequent droughts in this region had hindered its economic development and resulted in severe environmental problems [10]. Therefore, the temperature changes in the HHHPC are important to provide insight into linkage between climate change and agricultural production. Though long-term temperature trends are analyzed by many researchers in different regions [1, 11–15], there have been a few published studies focused on the temperature change in the HHHPC. Qu and Sun [16]

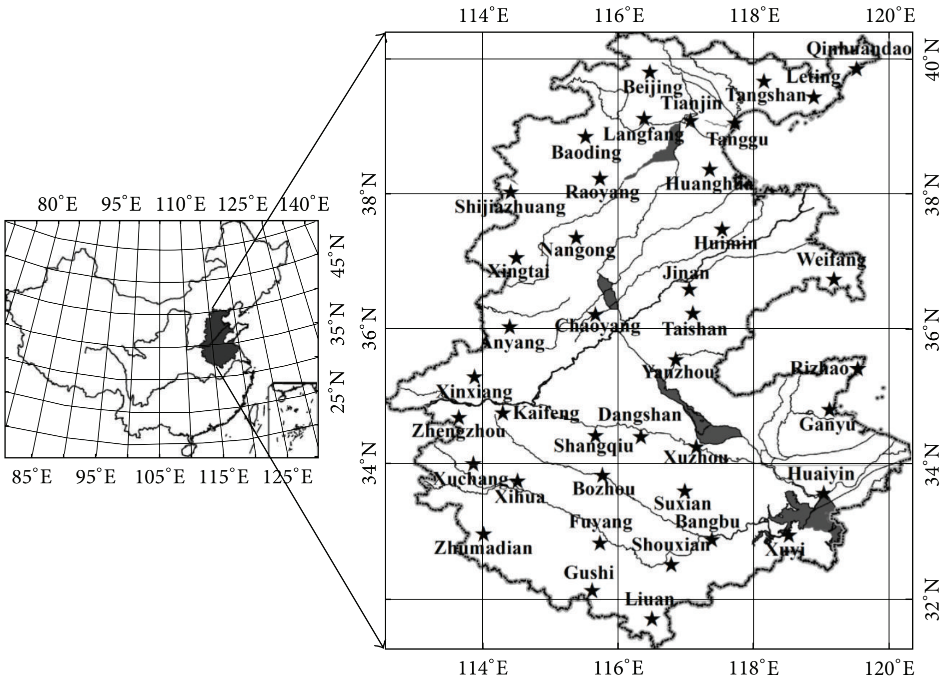


Figure 1: Distribution of 40 meteorological stations in the Huang-Huai-Hai Plain of China (HHHPC).

analyzed the characteristics of temperature variation form 1951 to 1988 and pointed out that the winter temperature was getting warming with time in the valley of the Huanghe-Huaihe-Haihe Rivers. Yang et al. [17] analyzed the spatiotemporal characteristics and jump features of annual temperature in the HHHPC during 1961~2010 and revealed that annual temperature had an increasing trend in general with the rate of 0.26°C $10a^{-1}$. In addition, Liu et al. [7] investigated the effects of climate change on grain production of a winter wheat-summer maize cropping system corresponding to the temperature rising 2°C and 5°C. Yan et al. [18] analyzed the drought evolution characteristics and precipitation intensity changes during alternating dry-wet changes in the Huang-Huai-Hai River basin. Shi et al. [10] discussed the roles of irrigation and urbanization on the regional temperature change over the HHHPC. In general, the trend-related studies about temperature in the HHHPC were concerned only for annual variations, while the seasonal changes had not been analyzed. In addition, the spatial and abrupt changes of temperature in the HHHPC were not considered in published literatures. Thus, thorough studies of temperature changes in the HHHPC still have not been conducted so far.

Due to this fact, based on a monthly dataset of temperature time series (1960–2012) in the HHHPC, the objectives of this study are to systematically investigate the long-term trends and abrupt changes of annual and seasonal temperature in both space and time. This paper is organized as follows. The details of study area, data, and methods are described in the following section. Results are provided in Section 3 followed by the discussions in Section 4. Section 5 contains the conclusions.

2. Data and Methods

2.1. Study Area. The HHHPC makes up part of eastern China and extends from 112°33′ ~120°17′E to 31°14′ ~40°25′N (Figure 1). The total area of HHHPC is 35.66×10^4 km^2, which is an alluvial plain developed by the intermittent flooding of the Huanghe, Huaihe, and Haihe rivers. Seven provinces are situated in the HHHPC, which are Beijing, Tianjin, Hebei, Shandong, Henan, Anhui, and Jiangsu.

The population in the HHHPC is densely concentrated in the northeastern edge, especially in the vicinity of the capital, Beijing. The altitude of almost the entire plain is below 50 m above sea level and the slope gradient is less than 3° [8]. The climate in the HHHPC is temperate, subhumid, and continental monsoon with a cumulative temperature (>0°C) from 4200 to 5500°C, a frost-free period of about 170 to 220 d, and average annual precipitation ranging between 500 and 800 mm [19]. The grain production accounts for 31% of production in China and therefore becomes one of the most productive agricultural regions [20]. Double cropping of winter wheat and summer maize is the main production system in the study area, which is mainly sustained by irrigation [10]. The intensive irrigation not only offsets the water deficit, but also maintains high crop yield in the HHHPC.

2.2. Data Sources and Processing. In order to get a credible estimation of temperature for the long-term trends, the 40 longest and most reliable meteorological stations are collected from the HHHPC. All the monthly temperature data in these stations are available from China Meteorological

Data Sharing Service System (http://cdc.cma.gov.cn/), and the temperature records are from January 1960 to December 2012. The distribution of 40 meteorological stations over the HHHPC is shown in Figure 1.

The temperature data were subdivided into meteorological seasons, with winter defined as being from December to February (next year), spring from March to May, summer from June to August, and autumn from September to November. All the basic monthly temperature records were averaged to get the seasonal and annual data for each station according to the standards of China Meteorological Administration. The mean temperature from 1981 to 2010 called the climate standard value, which was recommended by the World Meteorological Organization (WMO), was selected as the long-time average annual value in this study.

2.3. Methods

2.3.1. Methods for Trend Analysis. The methods of moving average and linear regression were used to analyze the temporal trends of temperature in this study.

Moving average is a data processing method of moving and filter. It can eliminate the random fluctuations in the statistical series through mean method and use the mean value to indicate the changing trends of time series [21, 22]. As for the series of x with the sample capacity of n, the mathematical expression of moving average series is as follows:

$$\widehat{x}_j = \frac{1}{k}\sum_{i=1}^{k} x_{i+j-1} \quad (j = 1, 2, \ldots, n-k+1). \tag{1}$$

In this mathematical expression, k is the moving length. Since a moving average of $k = 5$ could simply display the average observations [23], the moving average of five years was used to display the changing trend.

Linear regression is a common method for testing the long-term linear trend of climate. The equation of linear regression is as follows:

$$Y = a_0 + a_1 t. \tag{2}$$

In the above equation, Y is the temperature; t is the time (it is from 1960 to 2012 in this paper); a_0 is the regression constant; a_1 is the regression coefficient which reflects the rate of temperature changes (if $a_1 > 0$, it indicates Y that increases with time t; if $a_1 < 0$, it indicates that Y decreases with t); $a_1 \times 10$ represents the changing trend of temperature per decade. The linear regression equation was tested by SPSS 18.0 software.

2.3.2. Methods for Spatial Analysis. The spline interpolator is a general purpose interpolation method that fits a curvature surface through the input points. Spline interpolation is preferred over polynomial interpolation, because interpolation errors can be reduced, even using low-degree polynomials for the spline. In addition, spline interpolation avoids the problem of Runge's phenomenon, which occurs when interpolating between equidistant points with high-degree polynomials. So, spline interpolation method is best for varying surfaces such as elevation, water table heights, or pollution concentrations [24] and has been widely used in many studies in order to analyze the spatial distribution of climate change [25–28]. Moreover, Li et al. [29] concluded that spline method can well reflect the spatial distribution of temperature and precipitation in China. Thus, in order to obtain the spatial distribution of temperature changes in the HHHPC, the spline method was conducted to reflect the relative magnitude of temperature and associated variability. This method yields a smooth surface under the software of ESRI ArcGIS 10.0. The formula of the spline interpolator is as follows [24]:

$$Z = \sum_{i=1}^{n} a_i R(b_i) + T(x, y), \tag{3}$$

where Z is the value of weather constituent which will be forecasted, n is the number of weather stations which started meteorological observation, a_i is the coefficient fixed by a series of linear equations, b_i is distance from the forecasting point to the ith point, and the expressions of $R(b_i)$ and $T(x, y)$ are as follows:

$$\begin{aligned} R(b_i) &= \left(\frac{b^2}{4}\left[\ln\left[\frac{b}{2\pi}\right] + c - 1\right]\right. \\ &\quad \left. + d^2\left[k_0\left[\frac{b}{d}\right] + c + \ln\left[\frac{b}{2\pi}\right]\right]\right) \cdot (2\pi)^{-1} \\ T(x, y) &= f_1 + f_2 x + f_3 y, \end{aligned} \tag{4}$$

where d^2 is the weighting coefficient, b is the distance between observation point and forecasting point, k_0 is Bessel function after revision, c is a constant, and f is the coefficient of linear equations.

2.3.3. Methods for Abrupt Change Analysis. In this study, Mann-Kendall test and moving t-test were used to explore the abrupt change of temperature. The Mann-Kendall test, which was originally devised by Mann [30] as a nonparametric test for detecting trends and the distribution of the test statistic, derived by Kendall [31], is used to test the nonlinear trend as well as the turning point. This test has the advantage of not assuming any distribution form for the data and has similar power to its parametric competitors. Therefore, it is highly recommended for general use by the WMO and is widely used in the literature to analyze abrupt change in the climate data.

For a given time series x_n, which has n random samples, a rank-based procedure is constructed:

$$\begin{gathered} S_k = \sum_{i=1}^{k} r_i \quad (k = 2, 3, \ldots, n), \\ r_i = \begin{cases} +1 & \text{if } x_i > x_j \\ 0 & \text{if } x_i \le x_j \end{cases} \\ (j = 1, 2, \ldots, i). \end{gathered} \tag{5}$$

Under the hypothesis of a random sample with independent for time series, the test statistic, UF_k, is defined as

$$UF_k = \frac{[S_k - E(S_k)]}{\sqrt{\mathrm{Var}(S_k)}} \quad (k = 1, 2, \ldots, n), \tag{6}$$

where $UF_1 = 0$, $E(S_k)$ and $\mathrm{Var}(S_k)$ are average and variance of S_k. When the values of x_n are treated as a random sample and have the same continuous distribution, $E(S_k)$ and $\mathrm{Var}(S_k)$ could be calculated as follows:

$$\begin{aligned} E(S_k) &= \frac{n(n+1)}{4}, \\ \mathrm{Var}(S_k) &= \frac{n(n-1)(2n+5)}{72}. \end{aligned} \tag{7}$$

According to mathematical expression (6), UF_k and UB_k are calculated from the positive sequence and negative sequence. At the given significant level, UF_k and UB_k sequence curve and the lines of critical value are drawn in the same map. On the basis of positive or negative sequence curve passing the reliable lines, if there was only an obvious intersection point within the reliable lines, this intersection was abrupt change point and was significant at the given level. If the intersection points were beyond the reliable lines or there were several obvious intersection points within the reliable lines, they could not be sure for abrupt change points.

After Mann-Kendall test, the moving t-test method was used to detect the possible abrupt change points in order to enhance the assurance of abrupt change results. For a given time series x_n, which has n random samples, datum point was set by a given time. The samples of two subsequences before or after datum point were n_1 and n_2. $\overline{x}_1$ and $\overline{x}_2$ were the average of two subsequences, and s_1^2 and s_2^2 were the variance of two subsequences. Two statistic values were defined as follows [21]:

$$t = \frac{\overline{x}_1 - \overline{x}_2}{s \times \sqrt{1/n_1 + 1/n_2}}, \tag{8}$$

$$s = \sqrt{\frac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2}}. \tag{9}$$

There were three steps for moving t-test to detect the abrupt change. Firstly, the same lengths of two subsequences before or after datum point were defined; namely, $n_1 = n_2$. Secondly, according to mathematical expression (8), the statistic values of two subsequences were successively calculated by using moving method to continuously set datum point. Thirdly, the average values of two samples by continuous changing the length of subsequence before or after datum point were compared at given significant level. If $|t_i| < t_\alpha$, the temperature had abrupt change at the datum point.

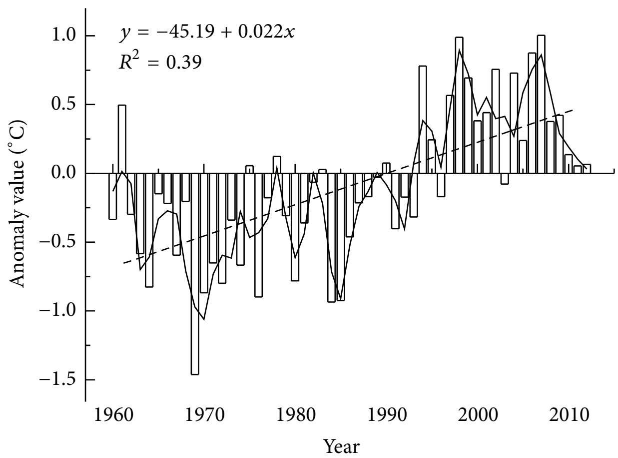
Moving t-test method could avoid the disruption by people for the selection of subsequence. Thus, the result detected by moving t-test was objective. In this study, the possible abrupt change points, which were detected by Mann-Kendall test, were taken as datum points. We continuously changed the length of subsequence before or after datum point. The minimum value of subsequence was 5 years, and its value increased year by year. If the results were significant at the level ($\alpha = 0.05$), the points could be regarded as abrupt change points.

3. Results

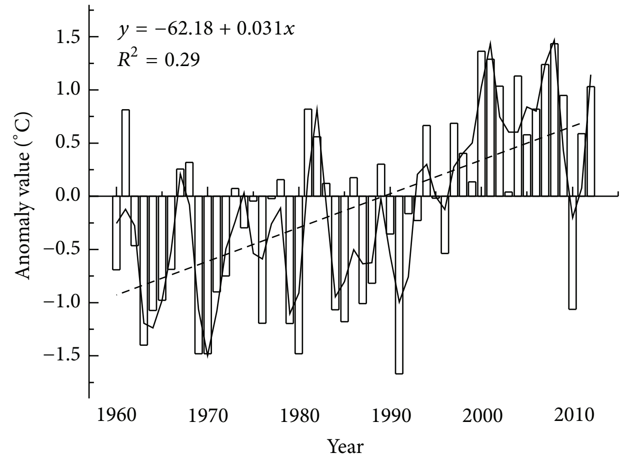
3.1. Trend Analysis of Temperature. The moving average and linear trends of annual and seasonal temperature in the HHHPC were shown in Figure 2. From Figure 2(a), annual temperature emerged as several big fluctuating changes during 1960~2012. It was fairly cold from 1960 to 1970 and relatively warm in the period of 1971~1980 and 1985~2009 (Figure 2(a)). Similar to annual temperature, the temperature in spring also showed fluctuating variations and had an obviously upward trend after the mid-1980s (Figure 2(b)). The temperature in summer had a process of decreasing (1965~1975), flatting (1976~1992), and increasing (after 1993) (Figure 2(c)). The autumn temperature remained a flatting process from 1960 to 1990 and was warm after 1990 (Figure 2(d)). As for the winter temperature, it had an evolution of cold (1962~1967), warm (1968~1978), cold (1979~1984), and warm changes (1985~1997), and the climate had two big fluctuation changes after 1998 (Figure 2(e)). In general, annual and seasonal temperature in the HHHPC had several cold and warm fluctuating changes during 1960~2012.

The increasing trends of annual and seasonal temperature were also reflected from Figure 2. According to Figure 2, the linear tendencies were northeast-southwest ward, which implicated that the regression coefficients of linear trend rate were above zero and the temperatures had an upward trend. Further analysis showed that the tendency rate of annual temperature was $0.22^\circ\mathrm{C}\ 10\mathrm{a}^{-1}$ ($P < 0.001$), which implicated that annual temperature had an obvious uptrend in the period 1960~2012, especially after 1990s. The linear trends of seasonal temperature were shown in Figures 2(b)~2(e), which indicated that seasonal temperature increased with different degrees. Significant increasing trends ($P < 0.001$) were found for winter ($0.34^\circ\mathrm{C}\ 10\mathrm{a}^{-1}$) temperature and spring ($0.31^\circ\mathrm{C}\ 10\mathrm{a}^{-1}$) temperature. A medium significant increasing trend ($P < 0.05$) was identified for autumn ($0.21^\circ\mathrm{C}\ 10\mathrm{a}^{-1}$) temperature, and no significant trend was seen for summer ($0.05^\circ\mathrm{C}\ 10\mathrm{a}^{-1}$) temperature.

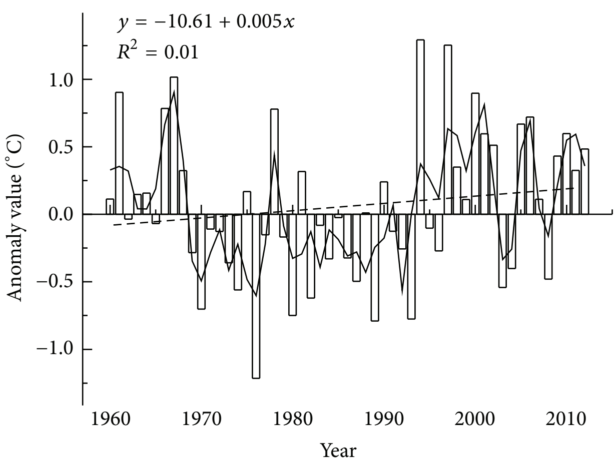
The interdecadal changes of annual and seasonal temperature were listed in Table 1. Table 1 implicated that annual temperature before the 1990s was relatively low, while it was fairly high after the 1990s. In particular, it was 0.27°C higher than the long-time average annual value after 2001. The spring temperature before 2000s was comparatively low, and it was 0.57°C higher than the long-time average value in the period of 2001~2012. The summer temperature was low in the 1970s and 1980s, while it was relatively high in the 1960s, 1990s, and 2000s. The autumn and winter temperatures were similar, which were fairly cold before the 1990s and relatively warm after the 1990s, and they were 0.29°C and 0.06°C higher than the long-time average value, respectively, in the period of 2001~2012.



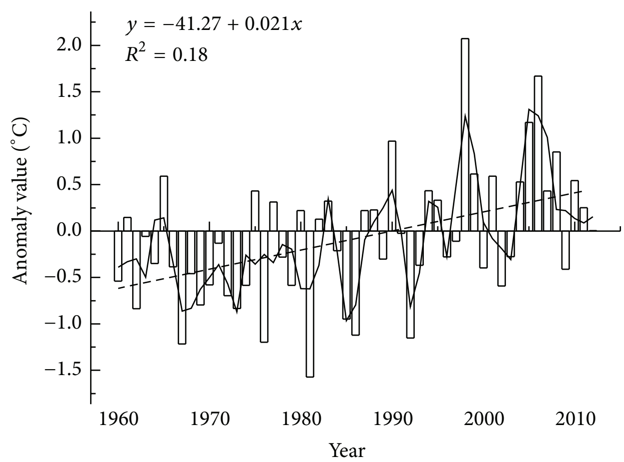
(a) Year in the HHHPC



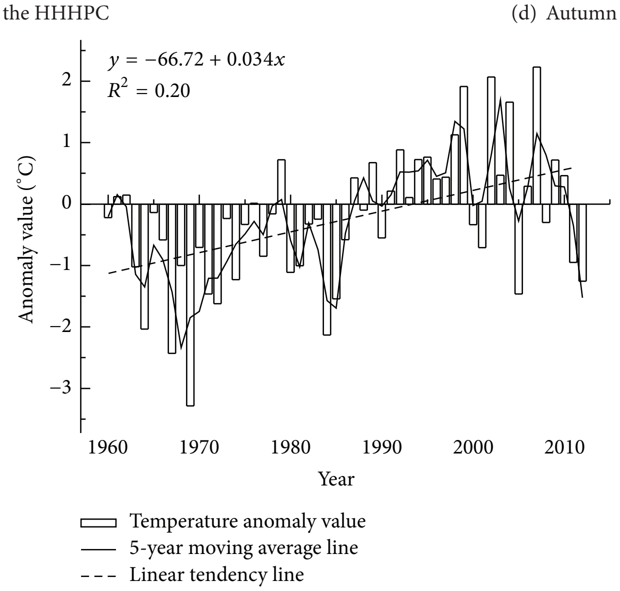
(b) Spring in the HHHPC



(c) Summer in the HHHPC



(d) Autumn in the HHHPC



(e) Winter in the HHHPC

FIGURE 2: Changes of annual and seasonal temperature in the HHHPC from 1960 to 2012.

Table 1: Annual and seasonal average temperature anomaly in the HHHPC.

Period	Spring (°C)	Summer (°C)	Autumn (°C)	Winter (°C)	Year (°C)
1960~1970	−0.81	0.13	−0.52	−1.22	−0.61
1971~1980	−0.75	−0.33	−0.45	−0.84	−0.59
1981~1990	−0.43	−0.29	−0.34	−0.75	−0.45
1991~2000	−0.12	0.15	0.00	0.41	0.11
2001~2012	0.57	0.17	0.29	0.06	0.27

In conclusion, annual and seasonal temperature had an uptrend in general during the process of obviously fluctuating variation in the period 1960~2012 and were relatively cold before the 1990s and fairly warm later in the 1990s and 2000s. The increasing trend of temperature was very significant in winter and spring, moderately significant in autumn, and nonsignificant in summer.

3.2. Spatial Analysis of Temperature. The spatial changes of annual and seasonal temperature in the HHHPC from 1960 to 2012 were shown in Figure 3. Figure 3(a) implicated that annual temperature increased with different rates, and the uptrend rates in most region of HHHPC were between 0.10°C $10a^{-1}$ and 0.30°C $10a^{-1}$. In addition, Figure 3(a) further revealed that the upward rate was the maximum in Beijing and its adjacent regions and was the minimum in the central region. The upward rates of annual temperature in the regions of Shijiazhuang, Leting, Xingtai, and Langfang were also big, and their rates were 0.35~0.43°C $10a^{-1}$ (Figure 3(a)).

Similar to annual temperature, the changes of seasonal temperature also had obviously spatial differences (Figures 3(b)~3(e)). The uptrend rates of spring temperature in most HHHPC were 0.11~0.52°C $10a^{-1}$ (Figure 3(b)). In addition, the increasing rates of spring temperature were above 0.45°C $10a^{-1}$ in the north, while they were relatively small in the central region (Figure 3(b)). Compared with the spring temperature, the uptrend rates of summer temperature were above 0.10°C $10a^{-1}$ in most region of HHHPC, but they were not obvious (Figure 3(c)). The uptrend rates in the north and northwest region of HHHPC were fairly high with the rate above 0.20°C $10a^{-1}$, while they were relatively low in the central and southern region with the rate below 0.10°C $10a^{-1}$ (Figure 3(c)). Similar to the spring temperature, the increasing trend of autumn temperature was also obvious, and the uptrend rates in most region of HHHPC were above 0.10°C $10a^{-1}$ (Figure 3(d)). The increasing rates in the central region of HHHPC were 0.05~0.10°C $10a^{-1}$, while they were above 0.25°C $10a^{-1}$ in the northern and western region (Figure 3(d)). The increasing trend of winter temperature in the whole HHHPC was very significant, and the upward rate approached 0.61°C $10a^{-1}$ in the Xingtai region. The increasing trends were also big in the northern and southern regions of HHHPC, where the upward rates were 0.45~0.60°C $10a^{-1}$ and 0.30~0.45°C $10a^{-1}$, respectively (Figure 3(e)). However, the uptrend rates in the regions of Xuchang, Tianjin, Anyang, and Gushi were in the range of 0.10~0.20°C $10a^{-1}$, which were relatively low (Figure 3(e)).

As a whole, except for summer temperature, annual and other seasonal temperatures had obvious increasing trends in the whole HHHPC. The spatial changes of seasonal and annual temperature were similar. The significant uptrend regions were mainly in Beijing and its adjacent regions, while the increasing rate was relatively low in the central and southern region.

3.3. Abrupt Change Analysis of Temperature. Abrupt change of temperature is a key factor for forecasting and simulating climate change. The abrupt changes of annual and seasonal temperature in the HHHPC were detected by Mann-Kendall test and moving t-test. There was only an intersection point within the reliable lines in 1987 for annual temperature from Figure 4(a) and the positive or negative sequence curves of annual temperature exceeded the reliable lines of significant level ($\alpha = 0.05$). This intersection was an obvious abrupt change point, which implicated that annual temperature had abrupt change phenomenon in 1987.

Similarly, Figure 4(b) showed that there was an intersection within the reliable lines between 1988 and 1989 for spring temperature, and the positive or negative sequence curves of annual temperature exceeded the reliable lines of significant level ($\alpha = 0.05$). So, this intersection was also an abrupt change point, which implicated that spring temperature had abrupt change phenomenon, and the climate was getting warmer since 1988. As for summer temperature, there were two intersection points within the reliable lines from Figure 4(c), which were possible abrupt change points. However, the two intersection points were not abrupt change points by using the moving t-test, which implicated there were no abrupt changes for summer temperature. Figure 4(d) showed that the positive and negative sequence curves had two intersection points beyond the reliable lines between 1960 and 1965, which were also possible abrupt change points. After detecting by moving t-test, the two intersection points were not abrupt change points. In addition, there was only an intersection point within the reliable lines between 1985 and 1986 from Figure 4(d), and the positive or negative sequence curves of autumn temperature exceeded the reliable lines of significant level ($\alpha = 0.05$). So, the intersection within the reliable lines was abrupt change point, which showed that autumn temperature had abrupt change between 1985 and 1986. Similar to autumn temperature, there were also two intersection points beyond the reliable lines between 1960

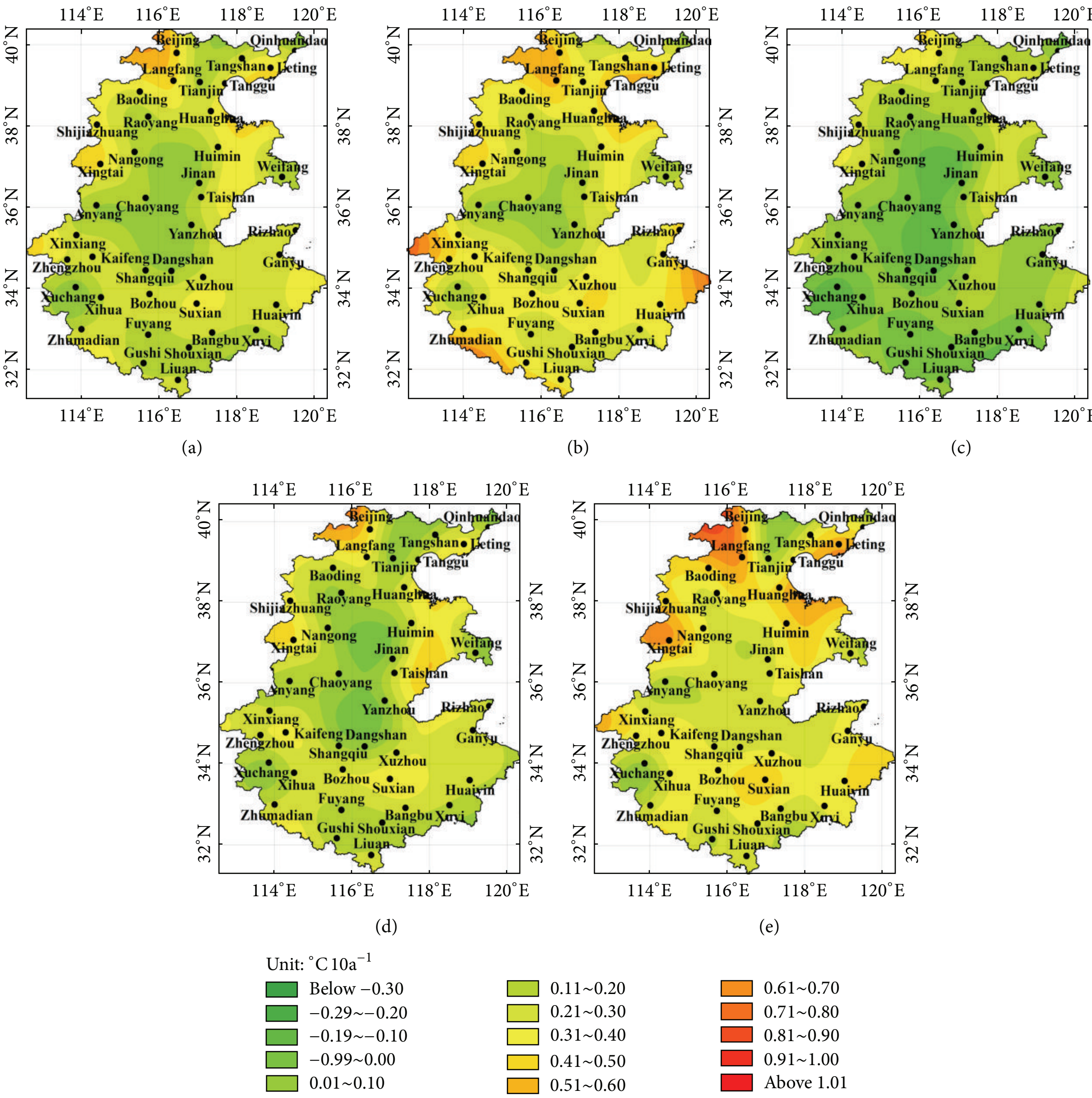


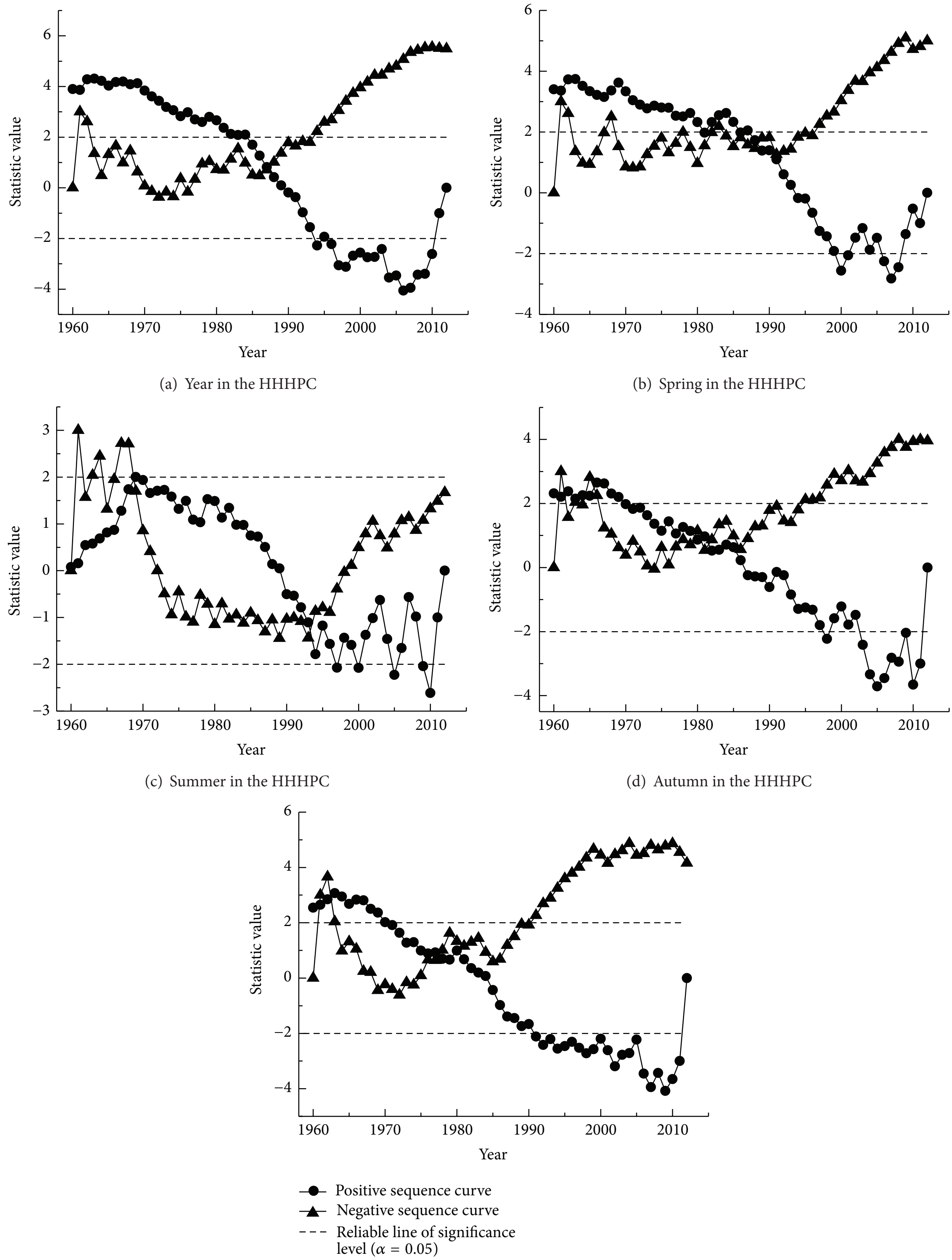
FIGURE 3: Spatial distribution of annual and seasonal temperature changes in the HHHPC during 1960∼2012.

and 1963, which were possible abrupt change points. The two intersection points beyond the reliable lines were not abrupt change points by using moving t-test (Figure 4(e)). Moreover, there was only an intersection point within the reliable lines between 1977 and 1978 for winter temperature from Figure 4(e), and the positive or negative sequence curves of winter temperature exceeded the reliable lines of significant level ($\alpha = 0.05$). Thus, the intersection within the reliable lines was abrupt change point, which implicated that winter temperature had warm abrupt change between 1977 and 1978.

Above all, except summer temperature, annual and other seasonal temperatures in the HHHPC had warm abrupt change. The temperature in winter had abrupt change in the late 1970s, while the abrupt change time of annual and other seasonal temperatures was in the late 1980s and early 1990s.

4. Discussions

Temperature change is a natural phenomenon, which is affected by many factors such as solar radiation, underling surface, topography, and human activities. Therefore, temperature would fluctuate randomly with various degrees for the different changes of above factors. In this study, long-term annual and seasonal temperature in the HHHPC had various changes with some oscillations from 1960 to 2012, which were consistent with most studies in other regions



(a) Year in the HHHPC

(b) Spring in the HHHPC

(c) Summer in the HHHPC

(d) Autumn in the HHHPC

(e) Winter in the HHHPC

FIGURE 4: Mann-Kendall test for abrupt changes of annual and seasonal temperature in the HHHPC.

[1, 27]. In addition, this research showed that the temperature in the HHHPC increased by the rate of 0.22°C $10a^{-1}$ during 1960~2012, which was close to the result by Tan et al. [12] and the same as the increasing rate in China from 1951 to 2001 [32]. Under the background of global warming, the temperature in the adjacent regions of HHHPC also revealed upward trends [1, 11–15]. It was well known that the temperature changes in the various regions would have some regional differences in the aspects of response to time, scale, and extent for the reason of climate background, regional characteristics, and climate driving forces. So, HHHPC became warmer and drier from 1960 to 2012 as a whole, which might respond to the global warming and regional warming in its adjacent regions.

As for the spatial differences of temperature change in the HHHPC, the significant uptrend regions of annual and seasonal temperature were mainly in Beijing and its adjacent regions, which might have some to do with the rapid urbanization. The rapid urbanization could alter the moisture flux associated with deep rooted trees and concrete [10], which in turn altered the local surface energy balance by increasing sensible heat flux and decreasing latent heat flux [33]. Latest research showed that the temperature changes had temporal consistency with the processes of urbanization in Beijing [34]. Therefore, urbanization induced heat islands, which could greatly influence natural variations in local climate [35] and was responsible for observed warming in the last few decades [36]. Published literatures [37, 38] showed that urban heat island had seasonal variations. The results in this study also implicated that urban heat island was obvious in winter, middle in spring and autumn, and not significant in summer. The seasonal variations of urban heat island in the HHHPC might have something to do with the large quantity of CO_2 and N_2O emissions during heating period, which started from November to March (next year). Previous study implicated that the concentration of greenhouse gas in heating period was higher 60~100% than nonheating period [39], which induced to obvious changes of temperature in winter, and was not significant in summer. In addition, this research also implicated that the increasing rate was relatively low in the central and southern regions, which are the main irrigated regions in the HHHPC. Many studies demonstrated that irrigation reduces soil albedo, increases transpiration and evaporation, and alters local soil moisture, energy balance, and climate [33, 40–43]. Further research indicated that irrigation had a significant cooling effect of 0.17~0.20°C $10a^{-1}$ on average daily maximum temperature and 0.12°C $10a^{-1}$ on summertime daily maximum temperature in the HHHPC [10]. So, the increase of irrigation since 1955 in the HHHPC [10] might be a major cause for its relatively low upward in the central and southern regions. Surely, there are few meteorological stations in the central and southern regions, which probably affected the interpolation results and showed relatively low uptrend.

This research implicated that annual and seasonal temperature in the HHHPC from 1960 to 2012 had abrupt change, except summer temperature. In addition, the temperature in winter had abrupt change in the late 1970s, while the abrupt change time of spring, autumn, winter, and annual temperature was in the late 1980s and early 1990s. All of these indicated that the temperature in the HHHPC increased quickly and entered into a relatively warm status. The abrupt change time of annual temperature was close to the northwest of China (early 1990s) [44] and the Qinghai-Tibet Plateau (middle of 1990s) [45], which implicated that the abrupt change of temperature had the responsibility and hysteresis in the HHHPC. The possible reasons for the temperature abrupt change in the HHHPC might have something to do with the large quantity of CO_2 and N_2O emissions [46], the change of land use type and the interior feedback process of the climate system [47]. However, the reasons of inducing to abrupt change of temperature were complex, which not only contained the macroscopic effect of global climate warming, but also included the effects of human activities. For the limit of data, the detailed reasons for the abrupt change of temperature in the HHHPC still needed to research further.

Published studies pointed out that climate warming could trigger large-scale changes in energy exchange processes and further affected the atmospheric circulation and regional precipitation patterns [48–50]. As an important region of intensive irrigation and productive agriculture, the climate warming in the HHHPC would influence the hydrological cycle and agricultural crops. On the one hand, it might lead to unexpected effects on the hydrological cycle if the temperature in the HHHPC increased gradually in the future. According to this study, annual temperature in the HHHPC would increase about 2°C in 2100 if it increased with the rate of 0.22°C $10a^{-1}$. The significant increasing trend of temperature would lead to the changes in soil moisture and further alter the amount of water available to plant roots [17]. In addition, the fluctuation of mean water table depth varies from −81 mm to 96 mm in the HHHPC if the temperature increases by 2~5°C and the precipitation increases or decreases by 15% [51]. On the other hand, the climate warming in the HHHPC would also affect the agricultural crops, which had positive and negative influences. Associated with the climate warming, the CO_2 content would increase, which could promote the photosynthesis of agricultural crops and further improve the production. Published study showed that the agricultural productivity potential increased 3.2% if the temperature increased 10% [52]. However, the climate warming could emerge drought easily and could further lead to the production reduction of agricultural crops. The spring drought in Henan province in 2009 is just a good example [53]. It was obvious that the climate warming in the HHHPC would have significant influences on other aspects. For the lack of data, the possible influences of climate warming in the HHHPC should be further research by quantitative analysis method in the future.

5. Conclusions

(1) Annual and seasonal temperature in the HHHPC increased with different rates during the process of fluctuating variation from 1960 to 2012, especially after 1990s. The upward rate was 0.22°C $10a^{-1}$ for

annual temperature, while it was very significant for winter ($0.34^{\circ}\mathrm{C}\ 10\mathrm{a}^{-1}$) temperature and spring ($0.31^{\circ}\mathrm{C}\ 10\mathrm{a}^{-1}$) temperature, moderately significant for autumn ($0.21^{\circ}\mathrm{C}\ 10\mathrm{a}^{-1}$) temperature, and nonsignificant for summer ($0.05^{\circ}\mathrm{C}\ 10\mathrm{a}^{-1}$) temperature.

(2) The seasonal temperature had similarly spatial changes to annual temperature. The significant uptrend regions of annual and seasonal temperature were mainly in Beijing and its adjacent regions, while the nonsignificant increasing regions were major in the central and southern region.

(3) Except the summer temperature, annual and other seasonal temperatures in the HHHPC had warm abrupt change. The temperature in winter had abrupt change in the late 1970s, while the abrupt change time of annual spring and autumn temperature was in the late 1980s and early 1990s.

(4) Macroscopic effects of global and regional climate warming and human activities (urbanization and irrigation) were possible reasons for the spatiotemporal changes of temperature in the HHHPC. The climate warming in the HHHPC would influence the hydrological cycle and agricultural crops.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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