

Spatiotemporal variation of precipitation based on three indicators in the flood season in Beijing

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Abstract. This paper attempts to analyze the spatiotemporal variation of precipitation in Beijing in terms of three indicators, i.e., the total precipitation, the maximum daily precipitation, and the maximum 5h precipitation in the flood season, with data collected from 20 meteorological stations from 1975 to 2012 (June to September). The Mann-Kendall non-parametric test, the linear regression, and five-year moving average were used. The results showed that: (i) the three indicators showed a decreasing trend; however, from 1975 to 1995 and from 1995 to 2012, the precipitation in the flood season showed an increasing trend with an increasing rate of 3.36 and 2.90mm/a, respectively. (ii) The indicators demonstrated a similar spatial variation. The high value precipitation areas were mainly in the northern and central parts of the city. The central districts had increasing centers with maximum increasing rates of 0.35, 0.65, and 0.49mm/a, respectively. However, the northern part exhibited different degrees of decreasing trends. (iii) The increase in the precipitation in the city center was mainly due to the urban heat island effect and the change in the underlying surface. The temperature gradient was intensified due to the topography in the city center and the northern suburb, causing a decreasing trend of precipitation.

1. Introduction

In Beijing, 80% of the precipitation falls in the flood season, when short-range strong rainfall often occurs. The rapid urbanization has led to an obvious change of precipitation in the downtown city. Precipitation is the key indicator in the water resource spatiotemporal pattern influenced by climate change. An extreme precipitation situation has a negative effect on the urban environment and the social economy. It is important to analyze the spatiotemporal distribution of precipitation in order to study the effect climate change has on water resource planning and management [1]. Therefore, this paper will study the extreme situations of precipitation, including the spatiotemporal variation of the maximum daily precipitation and the maximum 5h precipitation based on the study of the spatiotemporal distribution of the total precipitation in the flood season. It attempts to reveal the characteristics of the concentrated rainfall from three different time scales, which can help aid in understanding the characteristics of the extreme situation of precipitation and its future trend, to better allocate water resources, and to use the hydrological forecast to prevent flood and drought.

Currently, studies on the precipitation of Beijing mainly concentrate on the following aspects: (i) The first is studies focusing on the water distribution characteristics in the annual time scale [2]. For example, Xu Zongxue *et al.* used the non-parameter test method to analyze the spatiotemporal variation of the annual and interannual precipitation in Beijing. The result showed that the annual precipitation decreased over time in Beijing. (ii) The second is studies focusing on urbanization's



impact on precipitation [3, 4, 5, 6]. For example, Sun Jisong *et al.* analyzed the influence of the city island effect on the winter and summer precipitation in Beijing [7]. It was proposed that there is a clear difference in the relative variation trend of the precipitation days and the amount of city and suburbs in winter and summer. (iii) The third is studies focusing on the variation characteristics of the extreme precipitation [8, 9]. For example, You Huanling *et al.* analyzed the spatial distribution of the extreme precipitation characteristics. Their results indicated that from 1981 to 2001, the amount, days, and intensity of extreme precipitation showed a declining trend in most of the stations in Beijing [8]. The precipitation of Beijing mainly occurs in the flood season, which is usually accompanied with several great rainstorms that very likely result in flood disasters. In recent years, the precipitation has undergone distinct changes. However, the previous studies have mainly focused on the spatiotemporal variation of a long sequence of the annual precipitation in Beijing or only on the maximum daily precipitation, which fails to reflect the spatiotemporal variation of the concentrated precipitation of Beijing. Therefore, based on the precipitation data from 1975 to 2012, this paper attempts to analyze the spatiotemporal variation from three different times, i.e., the total precipitation, the maximum daily precipitation, and the maximum 5h precipitation in the flood season with the Mann-Kendall non-parametric test method, linear regression method, and the five-year moving average method. In terms of time, a comparison of long-sequence precipitation indicators and the variation of urbanization in different phases are analyzed. In terms of space, the distribution disparity and variation of the central urban area, the northern urban area, the southern plain area, and the western mountain area are analyzed, and potential explanations are given based on the analysis.

2. Materials and method

2.1. Study area

Beijing is located in the northern part of the North China Plain, surrounded by the Yanshan Mountains to the north and west and the Taihang Mountains in the northern section (figure 1). The mountainous area accounts for 62% of the entire region [10, 11]. It is a city of typical sub-humid continental monsoon climate in the North Temperate Zone, with great variation in annual precipitation and uneven precipitation distribution in the seasons. In summer, it is hot and rainy, whereas in winter, it is cold and dry. The multi-year average annual precipitation of Beijing is 585mm, among which the mountainous area is 591 mm, and the plain is 600mm. Approximately 80% of the precipitation falls in the flood season, which is 488 mm.

Song Xiaomeng *et al.* provided a potential method to divide Beijing into different zones [10]. Here, a similar approach is followed; Beijing is divided into six zones: the central urban area, northern urban area, suburb area, northern mountain area, western mountain area, and southern plain area (figure 1).

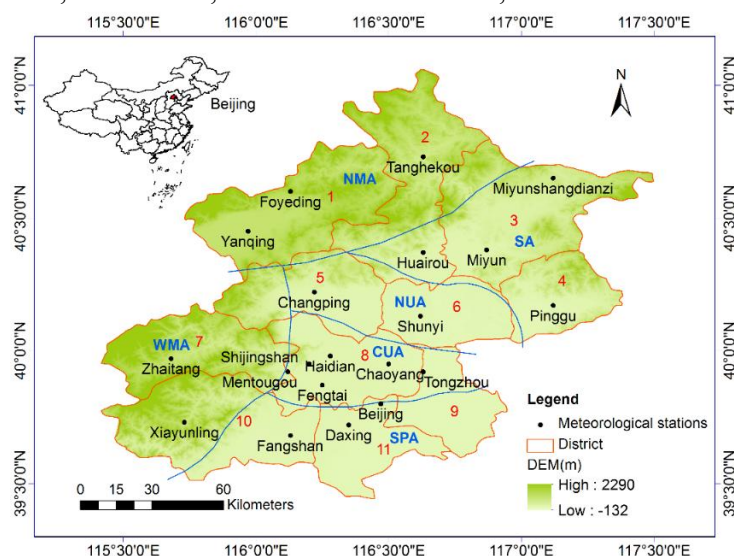


Figure 1. Distribution of the meteorological stations in Beijing. Blue solid lines denote the boundaries of six areas. CUA, NUA, SA, NMA, WMA, and SPA refer to the central urban area, northern urban area, suburb area, northern mountain area, western mountain area, and southern plain area, respectively. Numbers indicate different districts: 1. Yanqing; 2. Huairou; 3. Miyun; 4. Pinggu; 5. Changping; 6. Shunyi; 7. Mentougou; 8. Central city (including six districts: Dongcheng, Xicheng, Haidian, Chaoyang, Fengtai, and Shijingshan); 9. Tongzhou; 10. Fangshan; and 11. Daxing.

2.2. Data sources

The data of the paper were collected from the hourly precipitation records of 20 meteorological stations in Beijing from 1975 to 2012 as provided by the National Meteorological Administration. The stations include six from the urban area, eight from suburbs, and six from the mountain area, which covers the city center, suburb, and mountain area. The specific distribution is illustrated in figure 1. Both the Foyeding station and Xiayunling station have missing data for certain years, but this is corrected by interpolation and extension. Statistically speaking, the data is adequate to acquire a reliable result. This paper ascertains the monthly precipitation, the maximum daily precipitation, and the maximum 5h precipitation in the flood season based on the hourly precipitation data.

2.3. Method

In this paper, linear regression and the five-year moving average method are used to analyze the variation trend of the precipitation in the long-sequence and in twenty years in the flood season. The Mann-Kendall method was used together with the professional mapping software of Surfer 8.0, adapting the kriging spatial interpolation method to interpolate all the precipitation of all stations and the Mann-Kendall tendency rate to obtain the spatial distribution for analysis. The Mann-Kendall test sets up two series: a forward one (UF) and a backward one (UB). If the UF and UB curves intersect and then diverge and acquire specific threshold values, then a statistically significant trend exists. The point of intersection shows the approximate change point at which the trend begins [12-14].

3. Results and discussion

3.1. The temporal variation of the precipitation in the flood season

In order to eliminate the periodical variation of the data, this paper adopts the five-year moving average method to analyze the precipitation anomaly in Beijing and the five-year moving average variation trend (Figure 2). The precipitation time series below are based on the average of all 20 meteorological stations in each year.

From figure 2, it can be observed that: (i) The precipitation in the flood season is declining with time, yet the decline is not that obvious. The decrease rate for the multi-years average precipitation is 1.24mm/a, and the decrease rate for the 5-year moving average precipitation is 1.60mm/a. (ii). The precipitation anomalies before 1995 were mainly positive anomalies; afterwards, they were mainly negative. A distinct disparity exists before and after 1995. In figure 4, the UF and the UB curves indicating the average precipitation in the flood season also show a sudden change in 1995.

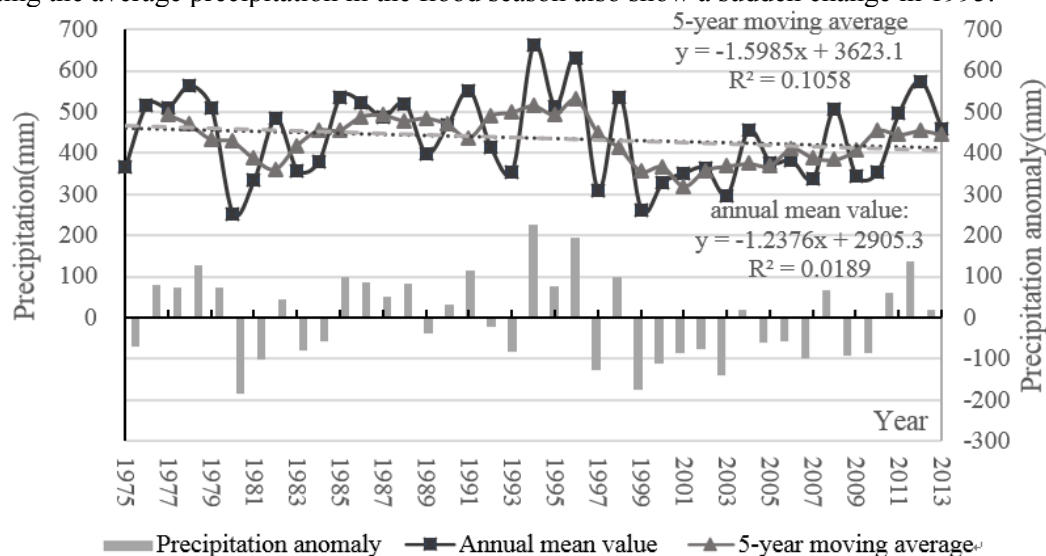


Figure 2. Temporal distribution and trends of rainfall in the flood season in Beijing.

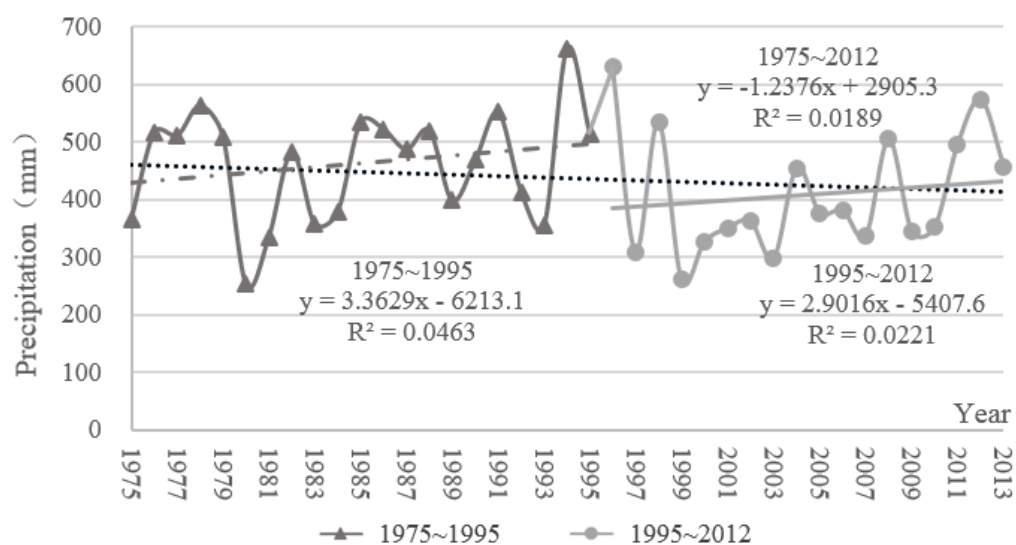


Figure 3. The linear variation trend of the precipitation in different periods in the flood season in Beijing.

Figure 3 illustrates the variation trends of the precipitation in different time periods. It can be found that in different time periods, the precipitation trends varied. Although the precipitation from 1995 to 2012 is less than that from 1975 to 1995, thus showing a decreasing trend in the long-sequence variation, there is clearly an increasing trend in these two periods at a rate of 3.36mm/a and 2.90mm/a, respectively. This reflects that the city island effect that emerged with rapid urbanization has little influence on the long-sequence precipitation trend, but it has a significant influence on the precipitation of certain areas in the most recent 20 years.

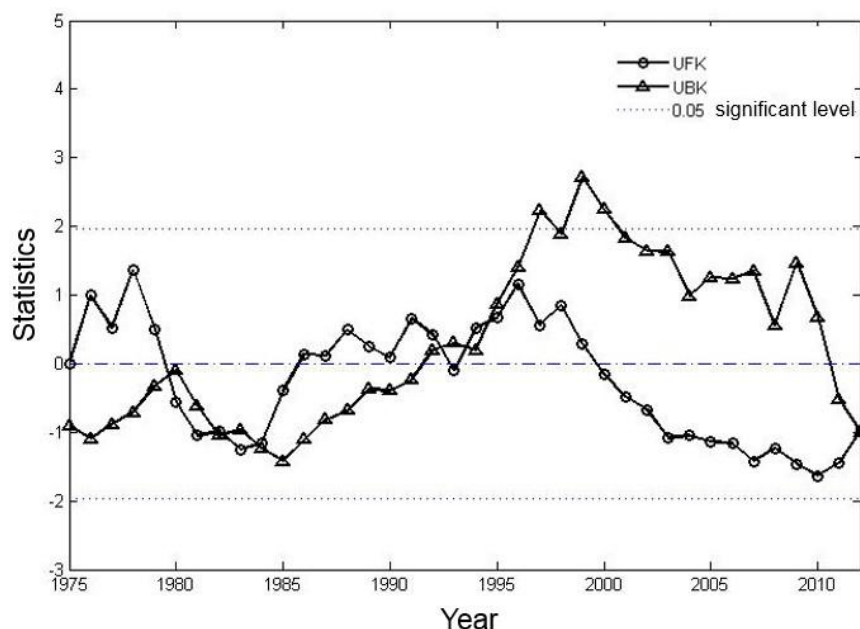


Figure 4. Mann-Kendall values of precipitation data series of flood season from 1975 to 2012 in Beijing.

In order to understand the variation trend of the monthly precipitation, a calculation is made on the statistical magnitude Z of Mann-Kendall and gradient β of the average precipitation month by month in the flood season. The result is shown in table 1. It can be concluded that: (i) the precipitation of the

flood season occurs mainly in July and August, which is when 38.6% and 31.1% of the flood season precipitation falls, and (ii) among the four monthly series, only August passes the significance level test ($\alpha=0.05$) and shows a decreasing trend. This indicates that August is the month that contributes the most to the decrease in precipitation in the flood season.

Table 1. The Mann-Kendall trend analysis of each month in the flood season.

Time sequence	The average precipitation (mm)	The parameter value of statistical characteristics		Trend
		Z	β	
Flood season	437.5	-0.895	-1	Tends to decrease
June	81.3	-0.251	-0.155	Tends to decrease
July	168.5	-0.226	-0.339	Tends to decrease
August	136.0	-2.816	-2.062	Distinct decrease
September	51.1	1.861	0.812	Tends to increase

3.2. The temporal variation of the extreme precipitation in the flood season

Due to the climate change, the intensity and the frequency of the hydrologic extremum have undergone changes. In recent years, Beijing has encountered many rainstorms, among which the “7.21” rainstorm produced the maximum precipitation in recorded meteorological history since 1951. To give context to the magnitude of the rainstorm, the average precipitation is 170 mm. However, during the rainstorm, the precipitation in the Fangshan district that was at the center of the rainstorm reached 541 mm, resulting in huge losses. Figures 5 and figure 6 show the variation trend of the maximum daily precipitation and the maximum 5h precipitation in the last 38 years in Beijing by using the linear regression method. Because 2012 was a year of extreme precipitation, it has a great impact on the analysis of the precipitation variation trend from 1995 to 2012. Therefore, it is excluded from the analysis. From the variation trend of the maximum daily precipitation in Figure 5, it can be observed that there is a decreasing trend either in the long-time sequence or in the 20-year time sequence in maximum daily precipitation, among which the decrease rate of 1995 to 2011 is 1.24mm/a. Its maximum daily precipitation is 7mm, which is less than that of 1975 to 1995. From the variation trend of the maximum 5h precipitation in Figure 6, it can be found that its variation trend is similar to that of the maximum daily precipitation. This is particularly distinct from 1975 to 2011 with a decreasing rate of 0.56mm/a.

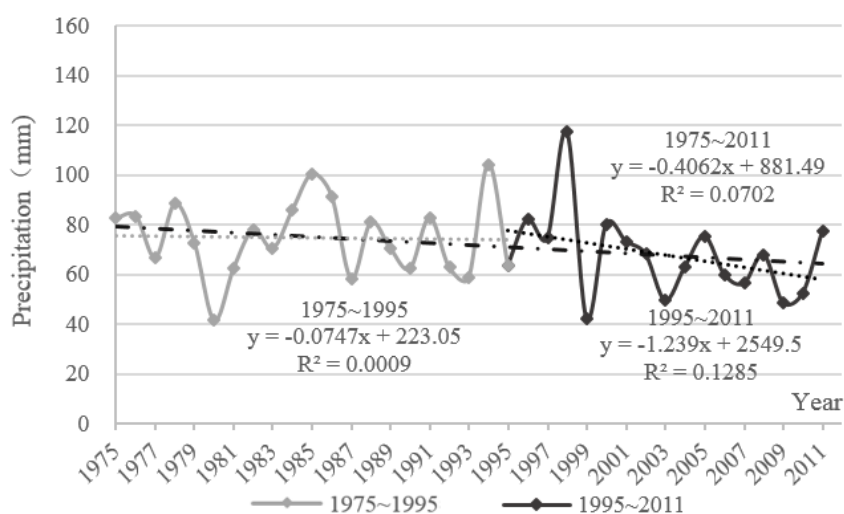


Figure 5. The variation trend of the maximum daily precipitation in Beijing from 1975 to 2011.

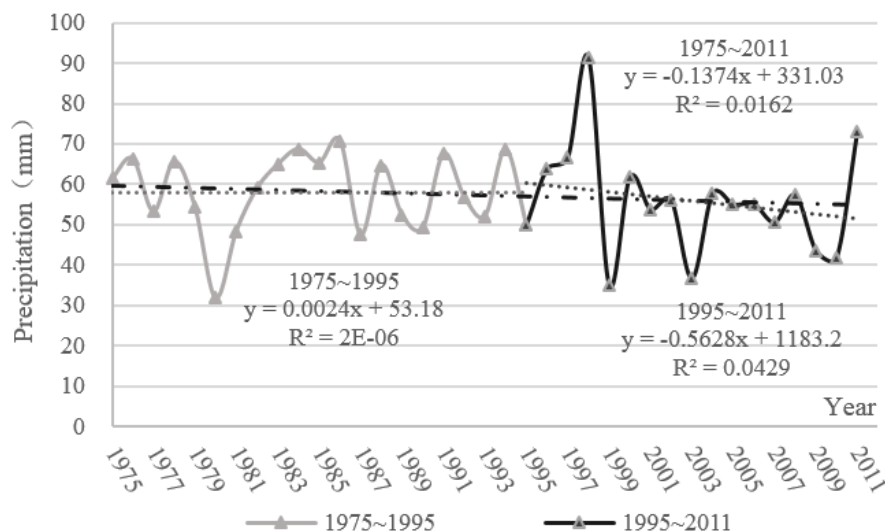


Figure 6. The variation trend of the maximum 5h precipitation in Beijing from 1975 to 2011.

3.3. The spatial variation of the precipitation in the flood season

From the long-time average precipitation contour map of Beijing in the flood season in figure 7, it can be observed that the precipitation of Beijing in the flood season is unevenly distributed. The high value districts of precipitation are mainly in the city center and the windward slope in front of the mountain in the northern part of the city. Generally speaking, the precipitation is decreasing from east to west. The precipitation in the southeast area is normally higher than 400mm, while the precipitation of the remote northwest area in the flood season is less than 400mm, among which the precipitation of the surrounding area of the Miyun district reaches 500mm.

From the Mann-Kendall gradient contour map of the long-term average precipitation in the flood season in figure 8, it can be observed that since the 1980s, different districts of Beijing have shown different degrees of a decreasing trend, among which the northern part of the city is the most obvious, forming a decreasing center in the Huairou district with a decrease rate of 4.8mm/a. However, in the city center, it exhibits a slight increasing trend, forming an increasing center in Haidian with an increase rate of 0.35mm/a. The west mountain area is quite stable.

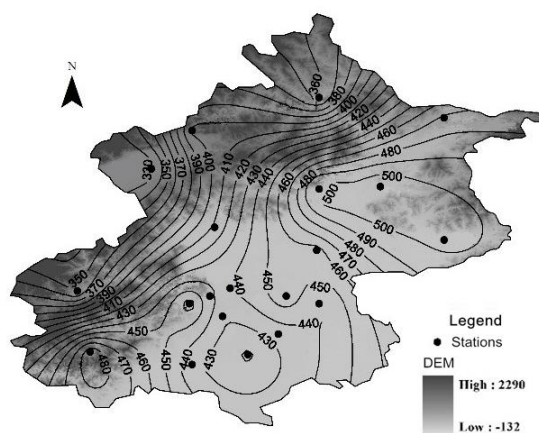


Figure 7. The long-time average precipitation contour map of Beijing in the flood season (mm).

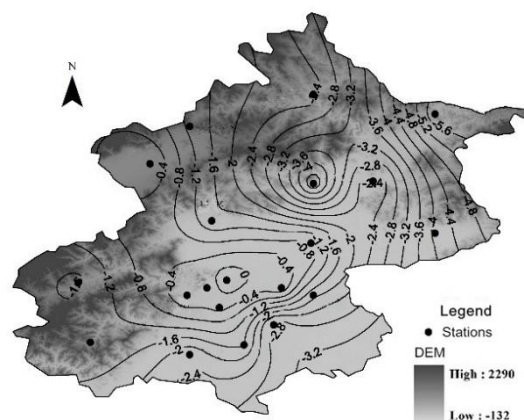


Figure 8. The Mann-Kendall gradient contour map of the long-term average precipitation in the flood season (mm/a).

3.4. The spatial variation of the extreme precipitation in the flood season

3.4.1. The spatial variation of the maximum daily precipitation. From figure 9, it can be found that the spatial distribution of the maximum daily precipitation is almost the same as the total precipitation in the flood season. The high value district is mainly in the city center, the northern part of the city, and the southern plain area, while the maximum daily precipitation is less in the western mountain area. From Figure 10, it can be found that there is a clear increasing trend in the city center, forming an increasing center in Mentougou with a maximum increasing rate of 0.65mm/a. The northern district and the mountainous area exhibit a clear decreasing trend, forming decreasing areas in Huairou and Miyun, with decreasing rates of 1.12mm/a and 0.03mm/a, respectively. The southern plain has no significant change. This result is in accordance with that proposed by You Huanling *et al.* [8]: the extreme precipitation intensity of the daily precipitation in the northern part of Beijing is decreasing, while the extreme precipitation intensity of the city center is increasing.

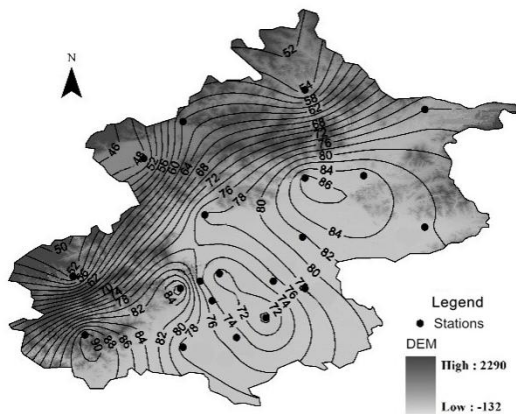


Figure 9. The contour map of the maximum daily precipitation of Beijing in the flood season (mm).

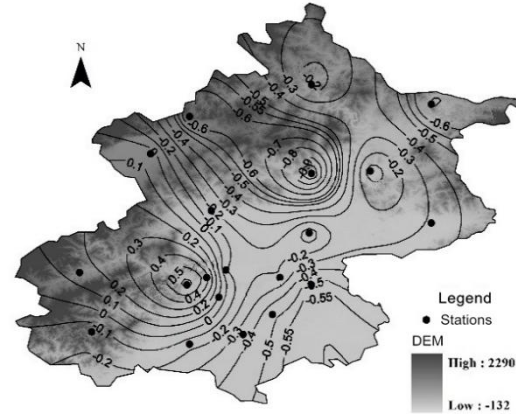


Figure 10. The Mann-Kendall gradient contour map of the maximum daily precipitation of Beijing in the flood season (mm/a).

3.4.2. The spatial variation of the maximum 5h precipitation

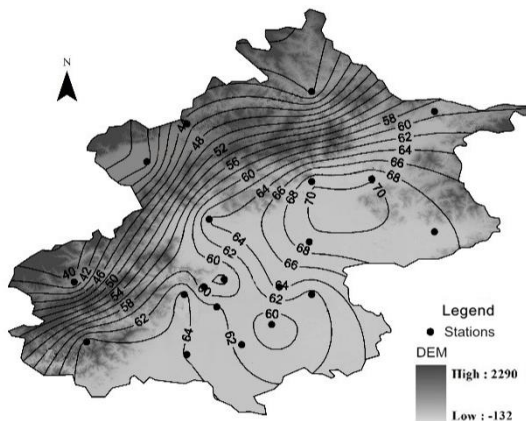


Figure 11. The contour map of the maximum 5h precipitation of Beijing in the flood season (mm).

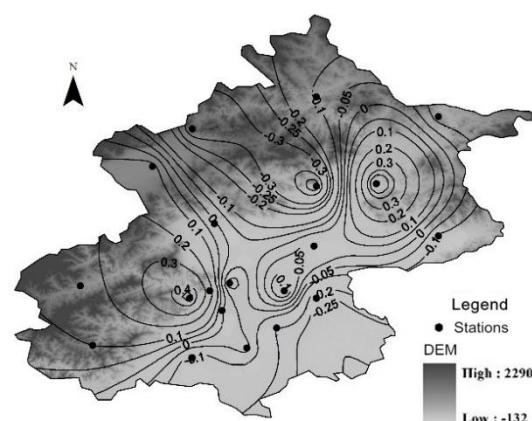


Figure 12. The Mann-Kendall gradient contour map of the maximum 5h precipitation of Beijing in the flood season (mm/a).

From figure 11, it can be found that there are two short-term rainstorm centers in the city center and its northern part, among which the maximum 5h precipitation in the north is 70mm/5h, and the

precipitation of the west mountainous area is 45mm/5h, which is relatively small. The precipitation decreases from east to west. From figure 12, it can be found that the city center and the northern part exhibit a clear increasing trend, forming two increasing centers in the Mentou Gou and Chaoyang districts with increasing rates of 0.49mm/a and 0.20mm/a, respectively. There is also an increasing center in Miyun with a rate of 0.56mm/a and a decreasing center in Huairou with a rate of 0.51mm/a in the northern part of the city. The variation trend is not obvious in the western mountainous area and the southern plain.

3.5. The preliminary analysis of the reasons of the spatiotemporal variation in the flood season

The spatiotemporal distribution of Beijing is influenced by various meteorological factors, such as the general atmospheric circulation, temperature, wind, and so on, as well as by underlying surface factors, such as the landscape, vegetation cover, and types of land utilization [4, 6, 15].

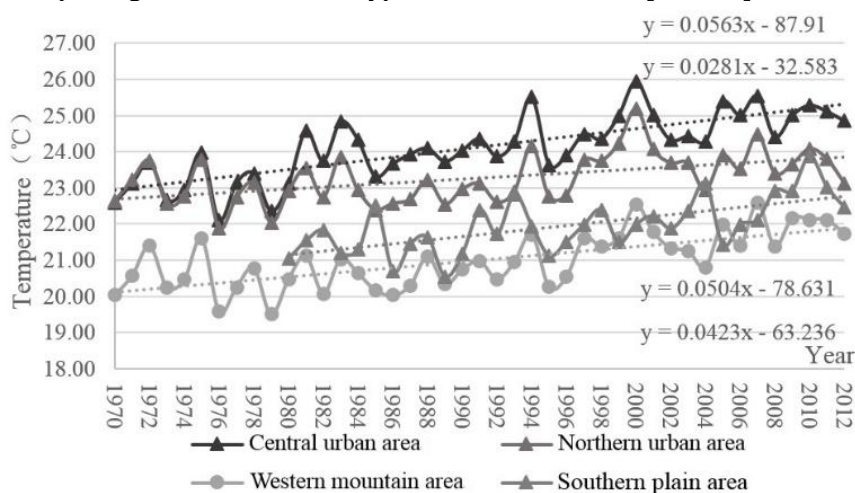


Figure 13. The temperature variation trend of different areas in Beijing.

Before 1980, the city of Beijing developed slowly. However, since 1980, Beijing has undergone rapid development [15]. The condition of the underlying surface became quite different from the suburb and the mountain areas due to the rapid expansion and development of the city. It can be observed from figure 13 that the temperature of Beijing increased differently in different zones. Since 1980, out of all the areas, the temperature of the city center increased the fastest with a rate of 0.56°C/10a and had the highest temperature. The temperature in the urban area was higher than that in the western mountain area and southern plain area. Sun *et al.* also found a variation in the temperature between the urban area and suburb, which explained the commonly observed ‘urban heat island effect’ [16]. This indicates that the urban heat island effect brought about by the urbanization and the variation of the underlying surface condition are probably the major factors that affect the precipitation variation trend and the long-term sequence variation in the last 20-years in the city center. The precipitation of the northern part of the city has remained at a high level. One possible cause of this phenomenon is that the topography has enhanced the temperature gradient between the city and the northern part. It would result in an increase in weak precipitation regions in the north [4]. In addition, the extreme precipitation intensity and the number of days decreased in the northern part of the city [4], which results in the decreased precipitation in the north. Because the southern part of the city is upstream of the city wind flow field, it is less influenced by the urban heat island effect, with no significant change in precipitation. The western mountain area is precipitous and is less influenced by the urban heat island circulation and monsoons. Therefore, the precipitation variation is not obvious.

4. Conclusions

This paper conducted the Mann-Kendall non-parametric test method, the linear regression method, and the five-year moving average method to analyze the spatiotemporal distribution features and the variation trend of the total precipitation, the maximum daily precipitation, and the maximum 5h precipitation in the last 38 years from 20 meteorological stations in Beijing. The following conclusions can be made based on the results:

- The precipitation in the flood season decreased with time in Beijing, with a rate of 1.43mm/a. This decrease resulted from the reduction of precipitation in August. However, 1975-1995 and 1995-2012 showed a clear increasing trend, with increase rates of 3.36 mm/a and 2.90mm/a, respectively. The maximum daily precipitation and the maximum 5h precipitation exhibited decreasing trends in three time periods. The decreasing rates of 1995-2011 were 1.24mm/a and 0.56mm/a, respectively.
- The spatiotemporal distribution of the precipitation in the flood season was unevenly distributed. The high value precipitation districts were mainly in the north and the center of the city, forming increasing centers with maximum increasing rates of 0.35mm/a, 0.65mm/a, and 0.49mm/a. In addition, the three time indicators in the north all had decreasing centers in the Huairou station, with decreasing rates of 4.8mm/a, 1.12mm/a, and 0.51mm/a. However, the maximum 5h precipitation resulted in increasing centers in the Miyun district, with an increasing rate of 0.56mm/a.
- The increasing trend of precipitation in the last 20 years in the city center was mainly caused by the heat island effect and the change to the underlying surface brought about by the rapid development of the city over the last 20 years. At the same time, this also increased the short-term strong precipitation in certain areas. Due to the topography, the northern part of the city has intensified the temperature gradient in the center city and the northern suburb. Meanwhile, because of the monsoons, the weak precipitation process in the northern part of the city increased, and the extreme precipitation decreased, resulting in a decreasing trend in the northern part of the city. Because the western mountain area was less influenced by the urban heat island circulation and the monsoon, the precipitation was in accordance with the decreasing trend with the long sequence precipitation.

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