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Analysis of Temporal Evolution Characteristics of Precipitation in Beijing

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Abstract: To master the law of precipitation evolution in Beijing and better implement the management of water resources. Based on the monthly precipitation data of Beijing from 1978 to 2020, the trend, mutation and periodicity of annual and seasonal precipitation in Beijing were studied by using linear regression, anomaly analysis, 5a moving average, Mann-Kendall mutation test and Morlet wavelet analysis. The results show that the annual, spring, summer, autumn and winter tilt rates are - 1.81mm/3a, - 0.17mm/3a, - 3.11 mm/3a, 1.42mm/3a and 0.02mm/3a respectively. The precipitation in summer decreased significantly in 2005, in autumn increased significantly in 2012, and in winter decreased significantly in 1982. There was no significant change in inter-annual and spring precipitation. The annual and seasonal precipitation had many mutations in this time series, and the mutations were 7 times, 13 times, 2 times, 5 times and 7 times respectively. There are three kinds of periodic changes in annual precipitation, and the intensity of periodic changes is the largest in the 20-32 year scale. There were 3 types, 2 types, 2 types and 2 types of periodic changes in each season respectively. The intensity of periodic changes in winter precipitation was the largest on a 10-20 year scale, and the intensity of periodic changes in the other three seasons was the largest on a 20-32 year scale. In general, the annual and seasonal precipitation in Beijing has obvious trends, mutations and periodicity, and the research results have certain reference values for Beijing water resources planning and other related work.

Key words: precipitation; Trend; Respectively; Periodically; Morlet wavelet analysis; M-K mutation test

Introduction

Water resources are an important guarantee for the stable development of our social economy and play a decisive role in the development of the region to a certain extent. Beijing is a severe water shortage area, per capita water resources are far less than the national average [1]. The amount of precipitation determines the allocation of water resources and the per capita water resources. From the existing water shortage situation in Beijing, it is of great practical significance to analyze the precipitation.

There are few studies on precipitation in Beijing: Zhao Haiming [2] et al, found that the spatial and temporal distribution of precipitation in the flood season of Beijing in 2019 was uneven. In terms of time distribution, there were fewer in the early and late stages and more in the main flood season. In terms of spatial distribution, precipitation showed a zonal distribution extending from southwest to northeast, and the precipitation in the plain was less than that in the mountain area. Han Li [3] et al. believed that the extreme precipitation series in Beijing had a significant downward trend, the possibility of drought on a monthly scale in the future decreased, and the possibility of flood disasters increased. Chen Yuanyuan [4] et al. pointed out that the pH value of precipitation in Beijing in spring and autumn showed an upward trend, and the pH value of precipitation in summer and winter showed a downward trend. Zhu Longteng [5] et al, found that most of the precipitation in Beijing is concentrated in summer, and the precipitation distribution is uneven during the year. The maximum daily precipitation and extreme heavy precipitation days showed a downward trend. Through R/S analysis, it is concluded that the future precipitation in Beijing is on the rise. The annual average temperature and the annual average maximum and minimum temperatures in Beijing have increased, and the annual average minimum temperature has the largest increase, followed by the annual average temperature, and the annual average maximum temperature is the smallest. Although the above research involves a wide range, there is no systematic analysis of the precipitation characteristics of Beijing. Because of this, this paper uses the linear regression method, anomaly analysis method, 5a moving average method, Mann-Kendall mutation test method and Morlet wavelet analysis method to study the trend, mutation and periodicity of annual and seasonal precipitation in Beijing, to provide a reference for water resources planning and other related work in Beijing.

1 Overview of the study

Beijing(115.7°-117.4° E , 39.4°-41.6° N) is located in the northern part of the North China Plain. Its land area is 16,412 km2, with a high proportion of mountains, high terrain in the northwest and low terrain in the southeast. It belongs to a warm temperate semi-humid and semi-arid monsoon climate, with high temperatures and rainy in summer and cold and dry in winter [6]. The annual average minimum temperature is 9°C, and the maximum temperature is 19°C. The precipitation is unevenly distributed throughout the year, and most of the precipitation is distributed in summer.

Since 2023, Beijing has been affected by external weather, coupled with less precipitation and other reasons, as of April 25, 2023, there have been four strong dust weather (Fig.1-2), during which there have been many times affected by external floating and sinking. After the deposition of external dust, dust will be repeatedly raised, resulting in ' secondary dust ' pollution. The effect of precipitation on soil and dust water content will directly reduce the formation of dust. Therefore, it is necessary to further analyze the precipitation characteristics of Beijing.

Fig.1 Weather conditions before the arrival of dust

Fig.2 Weather conditions after the arrival of dust

The pictures were taken in Haidian District of Beijing at about 11 a.m. on April 24 and 25, 2023.

2 Sources and Methods

2.1 Data source

The data used in this paper include monthly precipitation in Beijing from 1978 to 2020, which is from Beijing Meteorological Bureau. According to the reference [7], the seasons are divided into spring from March to May, summer from June to August, autumn from September to November and winter from December to February. At the same time, the annual and seasonal precipitation trends, mutability and precipitation cycle of Beijing were identified by various analysis methods.

2.2 Research method

After dividing the original precipitation data by season, the trend of annual and seasonal precipitation in Beijing was analyzed by the 5a moving average method [8-9], linear regression method [10] and anomaly analysis method [10]. The Mann-Kendall mutation test method [11-13] was used to detect the mutation characteristics of precipitation change, and the Morlet wavelet analysis method [14-16] was used to analyze the periodic change of precipitation.

2.2.1 Linear regression equation method

This method is a commonly used method to determine the changing trend of climate factors in long series. The formula is as follows:

$$P = at + b \quad (t = 1, 2, \ldots, n) \tag{1}$$

$$a_1 = 3 \cdot a \tag{2}$$

In the formula: P is precipitation(mm); ɑ is a linear trend; b is a constant; ɑ1 is the period precipitation tilt rate(mm/3a). If ɑ1 is negative, it means that precipitation decreases with time. If ɑ1 is positive, it means that precipitation increases with time.

2.2.2 Mann-Kendall mutation test method

Mann-Kendall mutation test is a non-parametric statistical test method. This method is less affected by a few outliers and is often used for mutation analysis and trend tests of hydrological series. The formula is as follows:

$$S_k = \sum_{i=1}^{k} r_i \quad (k = 2, 3, \ldots, n) \tag{3}$$

$$r_i = \begin{cases} 1 & x_i > x_j \\ 0 & x_i \le x_j \end{cases} \quad (j = 1, 2, \ldots, j) \tag{4}$$

$$UF_k = \frac{\left[S_k - E(S_k)\right]}{\sqrt{Var\left(S_k\right)}} \tag{1}$$

$$\beta = median\left(\frac{x_i - x_j}{i - j}\right) \quad \forall j < i \tag{2}$$

$$\begin{cases} UB_k = -UF_k \\ k = n + 1 - k \end{cases} \quad (k = 1, 2, ..., n) \tag{3}$$

$$\begin{cases} UB_k = -\alpha UF_k \\ k = n + 1 - k \end{cases} \quad (k = 1, 2, ..., n) \tag{4}$$

In the formula: Sk is the cumulative value of the number of values at the time i greater than the number of values at time j; E (Sk) is the mean value of Sk; var (Sk) is the variance of Sk; the median is the median function.

2.2.3 Morlet wavelet analysis

Morlet wavelet analysis can better analyze the evolution characteristics of meteorological elements at multiple time scales. This method is usually used to analyze the periodic changes of meteorological elements at different time scales. The formula is as follows:

$$\varphi_{a,b}(t) = \frac{1}{\sqrt{t}}\varphi\left(\frac{t-b}{a}\right) \quad (a, b \in R, a > 0) \tag{5}$$

$$W_f(a,b) = \langle f(t), \varphi_{a,b}(t) \rangle \tag{6}$$

$$W_f(a,b) = \frac{1}{\sqrt{a}}\int_R f(t)\varphi\left(\frac{t-b}{a}\right)dt \tag{7}$$

$$Var(a) = \int_{-\infty}^{+\infty} \left|W_f(a,b)\right|^2 db \tag{8}$$

In the formula: α is the scale factor; b is the translational factor; Wf (α, b) is the wavelet transform coefficient; Var(α) is the wavelet variance.

3 Analysis of precipitation time series evolution

3.1 Precipitation trend analysis

3.1.1 Annual precipitation trend change

The trend of annual precipitation characteristics in Beijing is shown in Fig.3. It can be seen from Fig.3 that the annual maximum precipitation in Beijing is 813.2mm, the annual minimum precipitation is 266.9mm, the annual average precipitation is 544.3mm, and the maximum value is about 3 times of the minimum value. The linear tilt rate of annual precipitation change is about - 1.8mm/3a, showing a slow decreasing trend year by year. It can be seen from the anomaly value and the 5a moving average line in the figure that the annual precipitation (1978-1999) changes more frequently, but the precipitation anomaly generally shows a positive value. The precipitation from 1999 to 2008 showed a "dry" state, and the precipitation anomaly from 2008 to 2020 was positive and negative, which was in a state of frequent alternation of "dry".

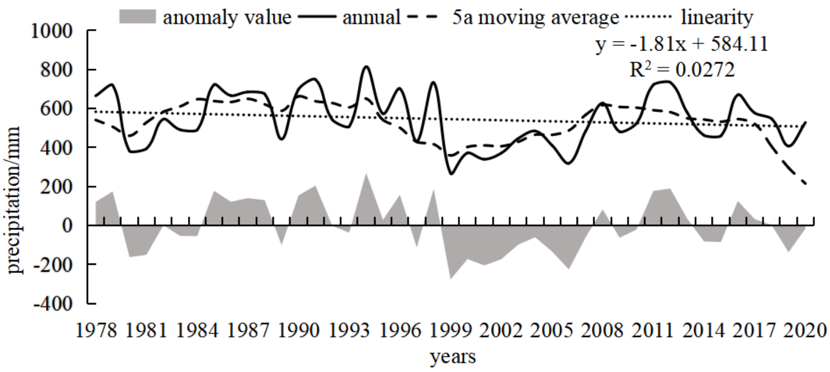


Fig.3 Annual variation of precipitation in Beijing

3.1.2 Seasonal precipitation trends

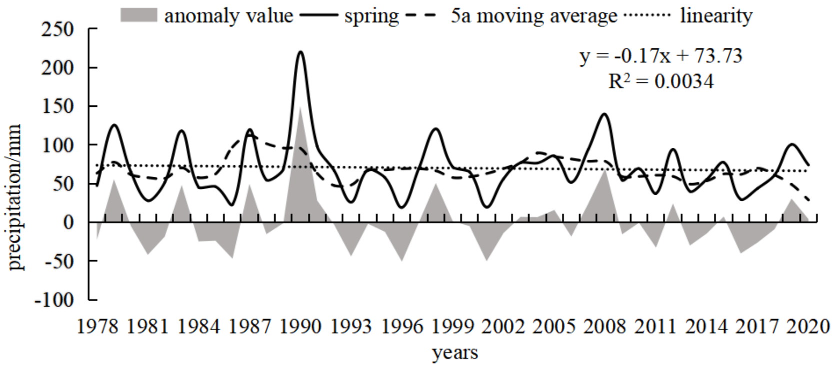
The trend of seasonal precipitation in Beijing is shown in Fig.4. It can be seen from figure 4:

(1) The maximum precipitation in spring is 219.8 mm, and the minimum precipitation is 19mm; the linear tilt rate of precipitation change is about - 0.17mm/3a, showing a slight downward trend. Precipitation is in a state of frequent alternation of "wet and dry ", and the amount of " wet and dry " precipitation from 1978 to 2020 is roughly offset and in a balanced state.

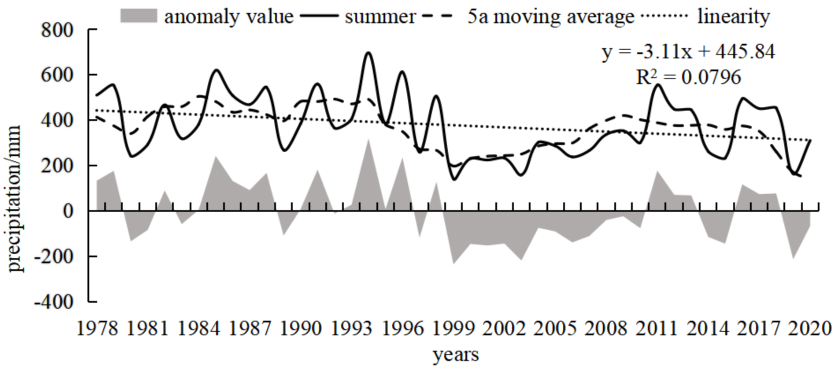
(2) The summer precipitation is between 140.6mm and 697mm, and the variation range is large. The linear tilt rate of precipitation change is about - 3.11mm/3a, showing a significant downward trend. From 1978 to 1985, the amount of "wet and dry" precipitation was roughly offset. From 1985 to 1999, the frequency of "wet and dry" precipitation decreased, and then the precipitation was a "dry" water period from 1999 to 2011. From 2011 to 2020, the precipitation "wet and dry" alternated, which was in the "flat" water period of precipitation.

(3) Autumn precipitation ranged from 9.4mm to 197.6mm. Precipitation changes showed a steady upward trend; the precipitation in 1978-1986 was in the "dry" water period, and then the precipitation changed from the fluctuating "flat" water period (1986-2007) to the "wet" water period (2006-2020).

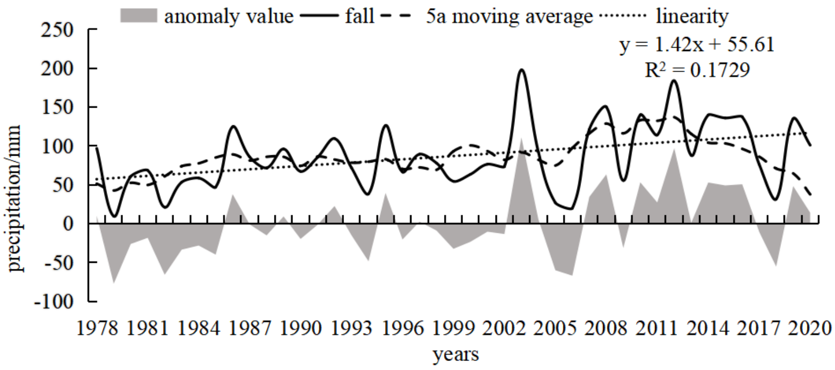
(4) The maximum precipitation in winter is 48.1mm, and the minimum precipitation is 0.3mm. Precipitation changes are basically in a stable state; the variation range of precipitation "wet and dry" decreased, and the positive and negative precipitation anomalies generally offset each other.



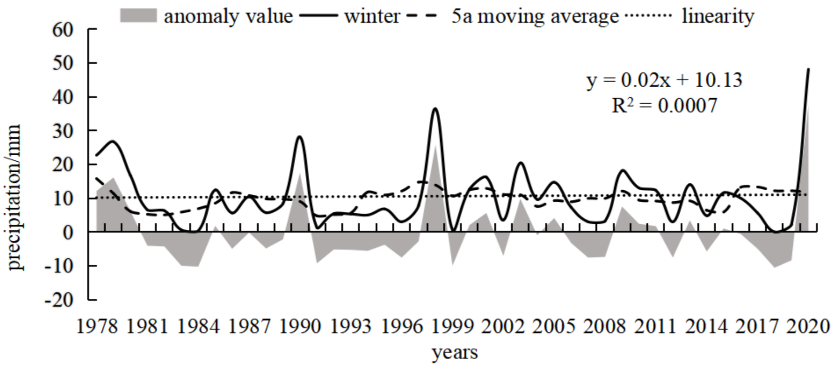
(a) spring



(b) summer



(c) fall



(d) winter

Fig.4 Seasonal variation of precipitation in Beijing

3.2 Catastrophe analysis

3.2.1 Annual precipitation mutation

The annual precipitation in Beijing was analyzed by M-K mutation test, and the UF and UB values of each period were calculated, as shown in Fig.5. The location of the intersection point in Figure 5 is used to determine the year of the mutation. Due to the wide range of M-K mutation test, to make the results more objective, it is necessary to combine the 5a moving average and the anomaly value (Fig 3) to assist the analysis, to determine the mutation years of precipitation in different periods.

It can be seen from Figure 3 and Figure 5 that the annual precipitation increased first and then decreased during 1978-1985. After 1985, it showed an upward state, and it continued to decline until about 2000. There was an intersection between the sequential statistical curve UF and the reverse statistical curve UB in the critical line interval of the significance level of 0.05. Therefore, the annual precipitation changed abruptly in 1980,1981,1996,2010,2013,2015 and 2018.

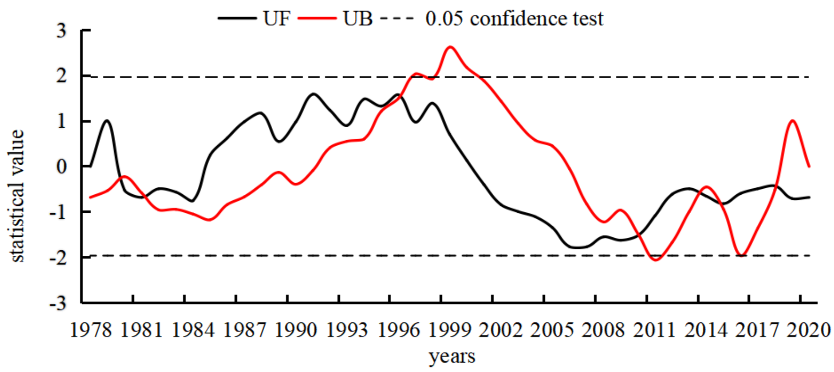


Fig.5 Mutation test results of annual precipitation in Beijing

3.2.2 Seasonal precipitation mutation

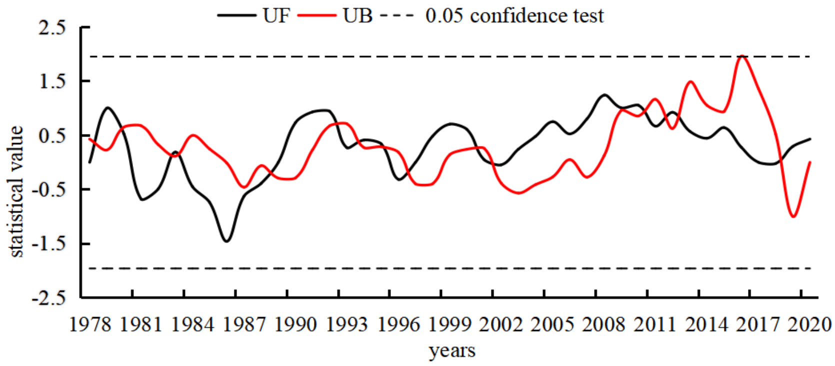
The results of the abrupt change analysis of seasonal precipitation are shown in Figure 6. It can be seen from the diagram:

(1) The spring precipitation showed a fluctuating state before 2002. During this period, the abrupt change years of precipitation were 1979, 1980, 1988, 1992, 1994, 1995, 1997, 2000 and 2001. After 2002, it showed an upward trend. During this period, the years with abrupt changes in precipitation were 2009, 2010, 2012 and 2018.

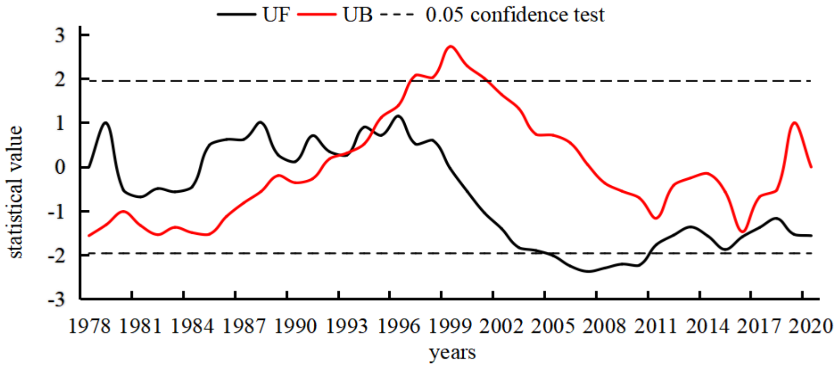
(2) The summer precipitation was in a state of fluctuation before 1984, increased between 1984 and 1999, decreased after 1999 and continued until 2020. The precipitation exceeded the 0.05 critical line of the significant level in 2005 - 2011, showing a significant decrease. There was an intersection between the UF and UB curves, so the summer precipitation changed abruptly in 1993 and 1994.

(3) The autumn precipitation showed a downward trend before 1986 and began to rise after 1985 and continued until 2020. The precipitation exceeded the critical line of 0.05 at a significant level from 2012 to 2020, showing a significant downward trend. There was an intersection between the UF and UB curves, so the autumn precipitation changed abruptly in 1989, 1991, 1993, 1996 and 1999.

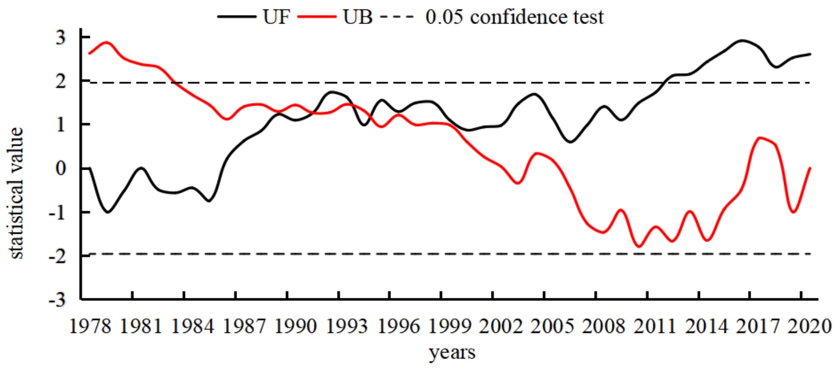
(4) The winter precipitation was rising from 1978 to 1979 and has been declining since 1979. It exceeded the critical line of significant level from 1982 to 1987, and the downward trend was significant. After 1987, the trend of UF curve increased, and the decreasing trend of precipitation decreased significantly. At the same time, there was an intersection between UF and UB curves. Therefore, the winter precipitation changed abruptly around 1998, 2000, 2002, 2006, 2012, 2014 and 2016.



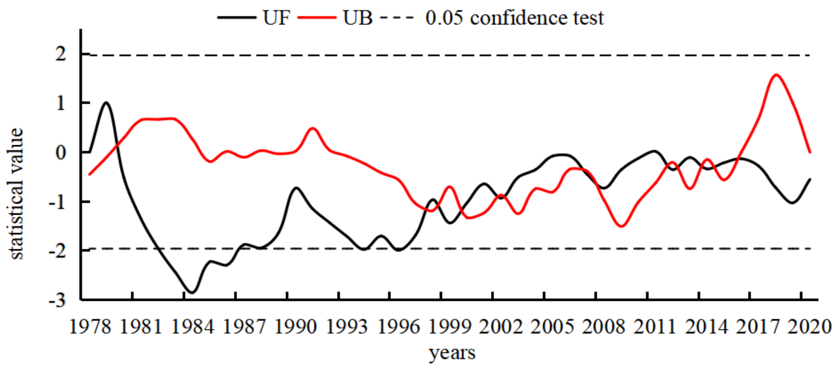
(a) spring



(b) summer



(c) fall



(d) winter

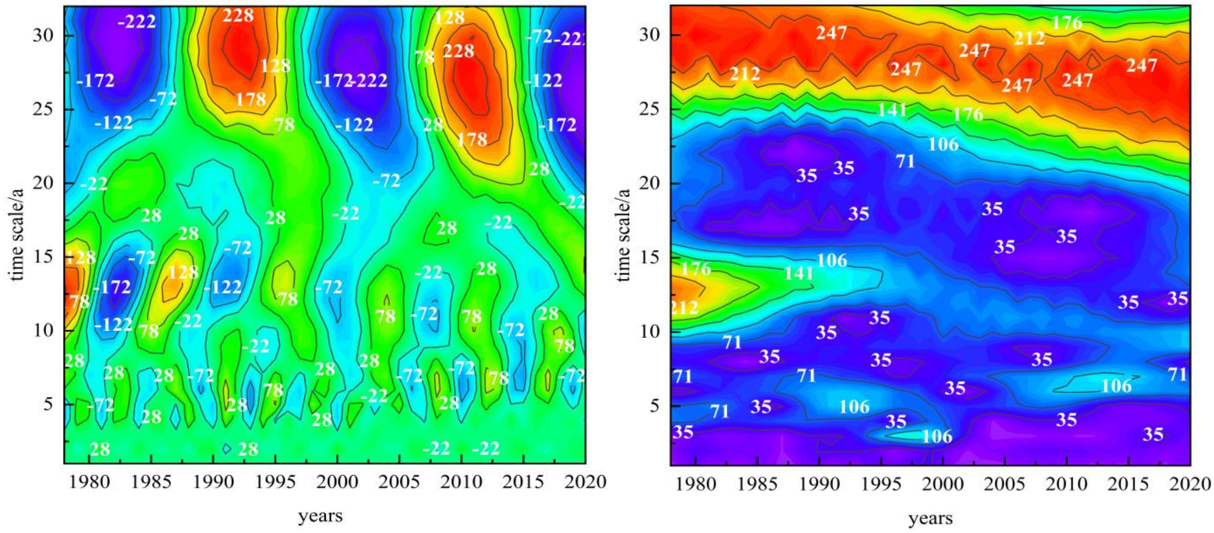
Fig.6 Mutation test results of seasonal precipitation in Beijing

3.3 Cycle analysis of precipitation

3.3.1 Analysis of the annual precipitation cycle

The Morlet wavelet is used to analyze the annual precipitation series in Beijing, and then the wavelet real part contour map, wavelet coefficient modulus contour map and wavelet variance map are obtained, as shown in Figs.7 and Figs.12. In Fig.7(a) when the real part of the wavelet is positive, it represents that the precipitation is more water period, and the negative value represents less water period. By summarizing the distribution of positive and negative values of the real part and combining the time scale, the multi-time scale characteristics of precipitation can be judged. In Fig.7(b), the modulus of the wavelet coefficient determines the distribution of energy density corresponding to different precipitation periods in the precipitation time series. The larger the modulus is, the more obvious the periodic change is in this time scale. In Figure 12, the distribution of the fluctuation energy of the precipitation time series on the time scale a can be judged according to the wavelet variance, and the existence of the main period and the sub-period in the precipitation time series can be determined by the number and size of the extreme values in the wavelet variance image.

It can be seen from Figure 7 that there are three types of periodic variation in the evolution of annual precipitation in Beijing, which are 2.5 - 7.5 years, 7.5 - 15 years and 20 - 32 years. Among them, precipitation showed 11 cycles of "more-less" on the 7.5 - 15 year scale, and 4 cycles of "less-more" on the 20 - 32 year scale. At the same time, it can be seen that the change of the 20 - 32 years scale is very stable and global in the whole analysis stage. In terms of periodic change intensity, the scale modulus of 20 - 32 years is the largest and the periodic change is the most obvious. It can be seen from Fig.11 that there are three extreme values on the wavelet variance curve of annual precipitation, corresponding to 7 years, 13 years and 28 years on the time scale. Among them, the extreme value corresponding to the 28-year time scale is the largest, indicating that the fluctuation energy oscillation is the most obvious, which is the first main cycle of annual precipitation change; the extreme value corresponding to the 13-year time scale is greater than the extreme value corresponding to the 7-year time scale, then the 13-year time scale is the second main cycle, and the 7-year time scale is the third main cycle.



(a) Morlet wavelet real part contour map (b) Morlet wavelet coefficient modulus contour map

Fig.7 Analysis results of the annual precipitation cycle in Beijing

3.3.2 Analysis of seasonal precipitation cycle

The results of the Morlet analysis of seasonal precipitation in Beijing and the Morlet wavelet variance diagram of seasonal precipitation (Figure 8-12) show that:

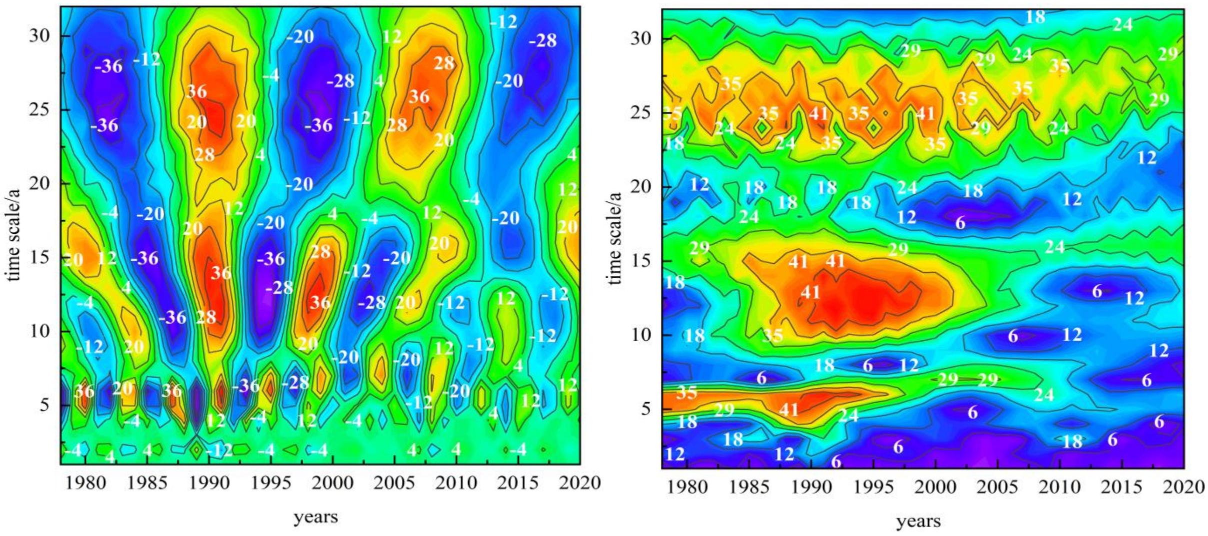
(1) There are three types of periodic variation of 2.5 - 7.5 years, 10 - 17.5 years and 20 - 32 years in spring precipitation. The periodic variation of the 20 - 32 year scale is the most obvious. The real part of the wavelet in the 10 - 17.5 year scale is highly closed, and the global characteristics are significant. In the 2.5 - 7.5 year scale, there is an alternating cycle of "less-more-less". The main period of precipitation is 26 years, and the sub-periods are 15 years, 12 years and 6 years respectively.

(2) Summer precipitation has two types of periodic variation of 7.5 - 15 years and 20 - 32 years. On the 20 - 32-year scale, the positive and negative phases alternate, and the precipitation shows an alternating cycle of "less-more", and the precipitation cycle changes most obviously at this scale. On the 7.5 - 15-year scale, there are 11 "more-less" alternating cycles and 10 oscillation centres of precipitation. The oscillation centres are in 1980, 1985, 1987, 1996, 2002, 2006, 2011, 2014, 2016 and 2019. The main period of precipitation is 28 years, and the secondary period is 13 years.

(3) The autumn precipitation is the most obvious in the 20 - 32 year scale precipitation cycle. On the 20 - 32 year scale, the precipitation is characterized by an alternating change of

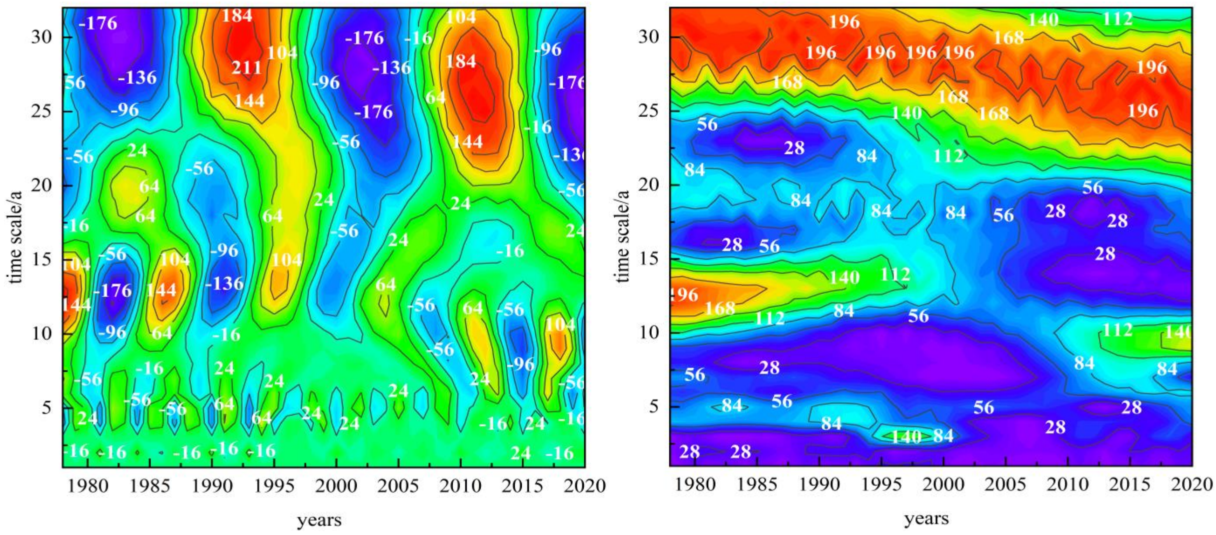
"less-more-less-more-less". There are five "more-less" alternating cycles and four oscillation centres. The oscillation centre is around 1986, 1996, 2006 and 2016. The main cycle of precipitation is 29 years, and the sub-cycles are 22 years, 13 years, 11 years, 9 years and 6 years.

(4) The two types of periodic variations of winter precipitation are 10 - 20 years and 27.5 - 32 years respectively. On the 10 - 20 year scale, the periodic variation of winter precipitation is the most obvious, showing an alternating state of "more-less" cycles. There are 9 "more-less " alternating cycles and 8 oscillation centres in precipitation. On the 27.5 - 32 year scale, the precipitation cycle presents a "more-less-more-less-more" cyclic alternating state. There are 5 "more-less" alternating cycles and 4 oscillation centres in precipitation. The oscillation centres are around 1983, 1993, 2005 and 2017. The main period of precipitation is 16 years.



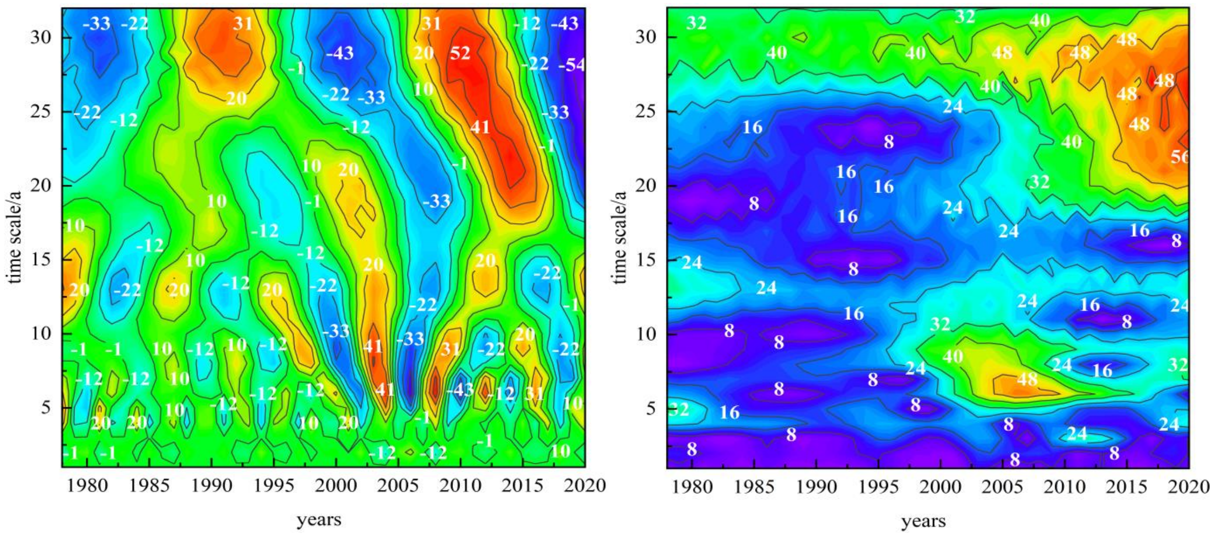
(a) Morlet wavelet real part contour map (b) Morlet wavelet coefficient modulus contour map

Fig.8 Analysis results of spring precipitation cycle in Beijing



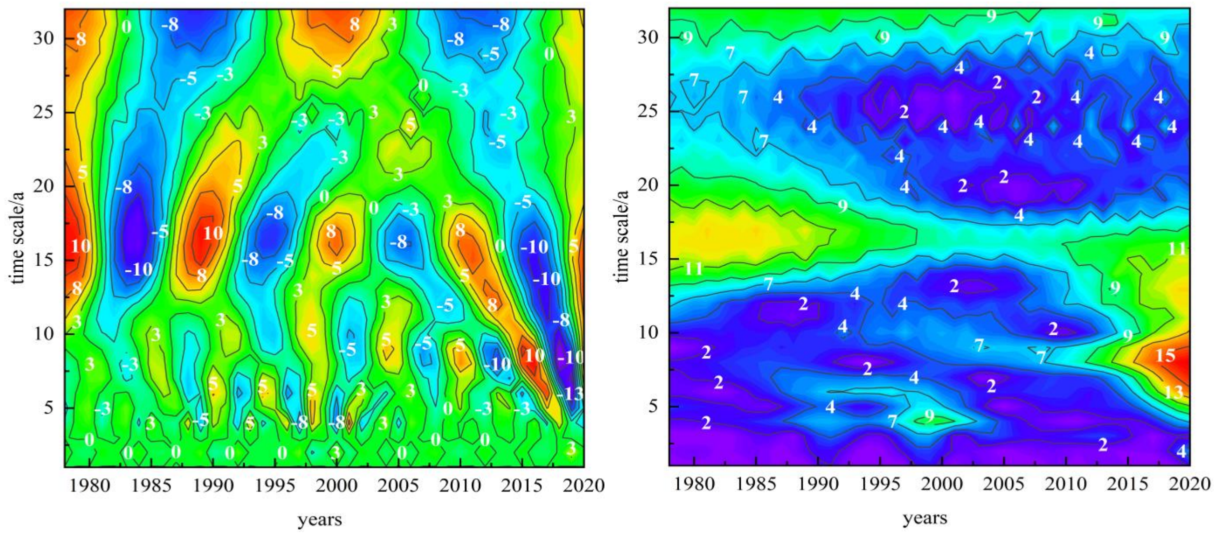
(a) Morlet wavelet real part contour map (b) Morlet wavelet coefficient modulus contour map

Fig.9 Analysis results of summer precipitation cycle in Beijing



(a) Morlet wavelet real part contour map (b) Morlet wavelet coefficient modulus contour map

Fig.10 Results of autumn precipitation cycle analysis in Beijing



(a) Morlet wavelet real part contour map (b) Morlet wavelet coefficient modulus contour map

Fig.11 Analysis results of winter precipitation cycle in Beijing

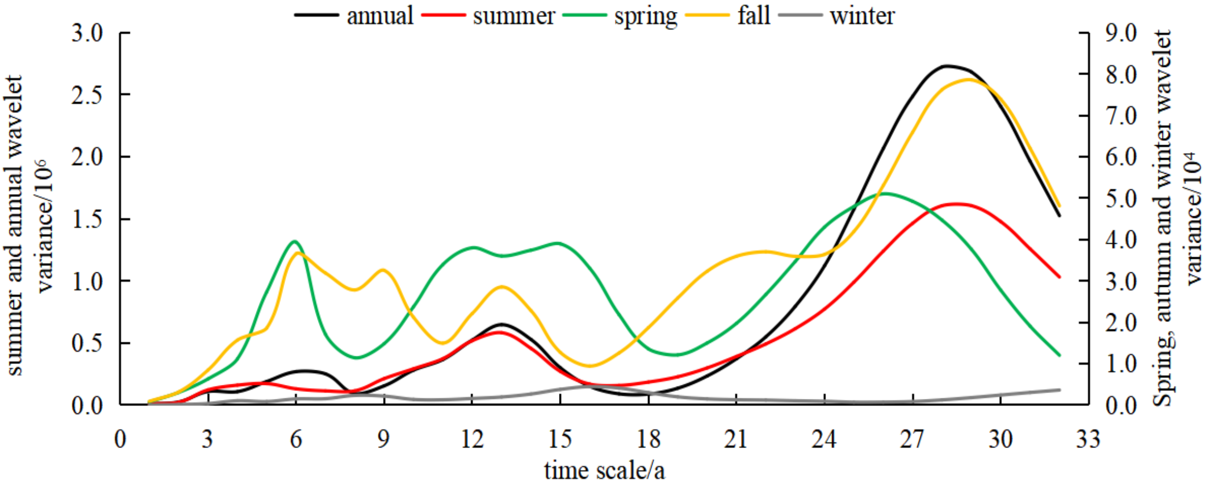


Fig.12 Morlet wavelet square difference diagram of precipitation in Beijing

4 Conclusion

At the level of periodic analysis, this paper combines the traditional wavelet real part value with the wavelet coefficient modulus to determine the intensity of periodic change. At the level of mutation analysis, the M-K test is combined with the 5a moving average and anomaly value to reduce the influence of the wide range of M-K test analysis. The results show that:

(1) The annual precipitation in Beijing decreased slowly year by year. The precipitation in spring and summer decreased year by year, and the precipitation in summer decreased greatly and exceeded the critical line of 0.05 at a significant level from 2005 to 2011. The precipitation in autumn increased year by year, but it exceeded the significance level of 0.05 critical line from 2012 to 2020, showing a significant decline. The winter precipitation showed a significant decrease from 1982 to 1987, but the tilt rate of its linear change was 0.02mm/3a, and the precipitation changed slightly on the selected time scale.

(2) The annual and seasonal precipitation in Beijing had multiple mutations in the selected time series, and the number of mutations was 7, 13, 2, 5 and 7 respectively.

(3) The main period of annual precipitation change in Beijing is 28 years, the second main period is 13 years, and the third main period is 7 years. The main period of spring precipitation change is 26 years, and the sub-periods are 15 years, 12 years and 6 years respectively. The main cycle of summer precipitation change is 28 years, and the sub cycle is 13 years. The main period of autumn precipitation change is 29 years, and the sub-periods are 22 years, 13 years,

11 years, 9 years and 6 years respectively. The main cycle of winter precipitation change is 16 years, and there is no obvious change in the sub-cycle.

This paper only studies the temporal variation characteristics of precipitation, and will further analyze the spatial variation of precipitation in the future, to accurately grasp the temporal and spatial variation characteristics of precipitation in the study area.

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