Evolution of meteorological factors during 1980–2015 in the Daqing River Basin, North China

Yufei Jiao, Jia Liu, Chuanzhe Li, Qingtai Qiu, Xiaojiao Zhang and Fuliang Yu

ABSTRACT

Precipitation and temperature data, such as the homogeneity, trend, abrupt change, and periodicity, obtained at 40 meteorological stations in the Daqing River Basin from 1980 to 2015 are analyzed using the Mann–Kendall method, anomaly accumulation, Rescaled range analysis (R/S analysis) and wavelet transform. The regularity of climate change is studied to provide guidelines for the rational utilization of water resources. The results show that the annual precipitation has an insignificant upward trend and suddenly changes in 2007. The precipitation evolution can be divided into three types of periodicity, that is, 22–32, 8–16, and 3–7 year time scales, where the 28 year scale is the first main period of precipitation change. The annual average temperature shows a notable upward trend, with 1992 as the change year. The annual average temperature can be divided into three types of periodicity, that is, the 25–32, 14–20, and 5–10 year time scales, where the 28 year scale is the first main period of temperature change. In conclusion, the climate of the Daqing River Basin gradually turns into humid and hot climate. The results provide valuable reference for the assessment of the effects of climate change, and the management of water resources.

Key words | abrupt change, periodicity, precipitation, temperature, trends

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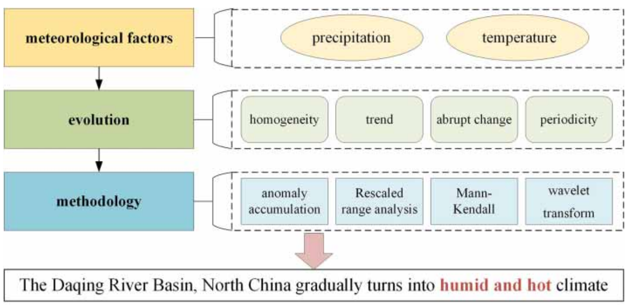
HIGHLIGHTS

- The evolution of precipitation and temperature is analyzed, including the homogeneity, trend, abrupt change, and periodicity, making use of the anomaly accumulation, Rescaled range analysis, Mann–Kendall method and wavelet transform in the Daqing River Basin, North China.
- The conclusion is that the climate of the Daqing River Basin gradually turns into humid and hot.

GRAPHICAL ABSTRACT



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INTRODUCTION

Global warming has proved to be an indubitable fact (Sharma & Goyal 2020). The increase in the temperature accelerates the hydrological cycle (Tian & Yang 2017). Precipitation is a considerable part of the hydrological cycle and the main source of surface runoff. Because of climate change, precipitation, that is, the precipitation frequency and intensity has significantly changed due to climate change. This change further aggravates the spatiotemporal difference in the distribution of precipitation, affects the rational utilization and planning of regional water resources, and influences the sustainable socio-economic development (Xu *et al.* 2018). Under the current climate change condition, it is particularly important to discuss the long-term effects of the climate change on the meteorological factors on the global and regional scales (Kukal & Irmak 2016). Previous studies showed that, the changes in air temperature and precipitation present different spatio-temporal trends at regional and global scales (Crowley 2000; Li *et al.* 2016). In addition, regional climate change leads to the increase in the occurrence of natural disasters, such as drought and flood, as a result of the imbalance of water resources (Yang & Lau 2004).

One of the most crucial elements of the complex hydrological environment is the temperature. A global increase in the temperature has been determined, which varies in space and time. Precipitation plays a prominent part in hydrological processes and is the important contributor to affecting the water balance (Yang *et al.* 2012; Dai 2013; Stocker *et al.* 2013). Studies showed that the precipitation increased throughout the 20th century in the whole world (IPCC 2007) (Solomon *et al.* 2007). Global land precipitation increased by approximately 2% over the 20th century (New *et al.* 2001). Analogue to the temperature, distinct temporal and spatial changes can be observed in the precipitation. Furthermore, precipitation strongly varies, even on a small scale (Kukal & Irmak 2016). Therefore, research on precipitation and temperature characteristics has gradually become a hot topic in the fields of meteorology, hydrology, and ecology. Scholars studied the precipitation and temperature on a global scale (Zhang *et al.* 2001; Aziz & Burn 2006; Sahoo & Smith 2009; Irmak *et al.* 2012; Wang *et al.* 2014). However, in recent years, it has been recognized that historical observations or future climate predictions at the global scale are meaningless for regional planning (Maier & Carpenter 2015). Therefore, historical trends and future predictions must be assessed at the regional scale. The Daqing River Basin in North China is selected as the research area, and it covers Shanxi, Hebei, Beijing, and Tianjin provinces. The Xiong'an New Area is situated at the hinterland of the Daqing River Basin.

Many scholars used Mann–Kendall test, Hurst index, Sen slope and other methods to study the evolution trends of meteorological factors in some basins of the world (Burn 1994; Jhajharia *et al.* 2009; Jones *et al.* 2015; Güçlü 2018). The Mann–Kendall test was employed to study the precipitation and temperature changes in Yangtze River, Yellow River, and Pearl River Basins of China from 1957 to 2013 (Tian *et al.* 2016). Martinez *et al.* used the data for Florida, and the Mann–Kendall method and Sen slope to evaluate the significance and magnitude of precipitation trends in the annual, seasonal, and monthly scales, and temperature in the average, maximum, minimum, and ranges (Martinez *et al.* 2012). Through combining the Discrete Wavelet Transform and Mann–Kendall method, to detect the monthly, quarterly, and annual trends of seven meteorological stations and eight runoff stations from 1954 to 2008 in Quebec and Ontario, Nalley *et al.* revealed that in general, intra- and inter-annual events (up to four years) are more influential in affecting the observed trends (Nalley *et al.* 2012). At the same time, some scholars studied the abrupt and periodicity of meteorological factors. The abrupt change of climate refers to the phenomenon that climate changes from one stable state to another. It shows a sharp change from one statistical feature to another in time and space. The abrupt change of climate can be classified into three types: mean abrupt change, rate abrupt change and trend abrupt change. It is characterized by non-linearity and multiple equilibria. Previous studies showed that the Tianshan Mountains had gone through a process of the rapid increase in temperature and humidity, with average warming and wetting rates of 0.32 °C/10 a and 5.82 mm/10 a, respectively, by examining the climate change as well as periodicity and temporal and spatial variability from 1960 to 2016 (Xu *et al.* 2018).

There are also more detailed studies, such as using indices to identify climate change, as well as the seasonal research on the trends of temperature and precipitation. Nine indices were applied to detect the drought and wetness cycle to determine the spatio-temporal precipitation and temperature characteristics in the Pearl River Basin in South China (Fischer *et al.* 2011). The changes of the temperature and precipitation at the annual and seasonal scales were studied from 1960 to 2008 in the Hengduan Mountain areas. The average annual, spring, summer, autumn, and winter temperatures exhibited markedly increasing by 0.15, 0.589, 0.153, 0.167, and 0.347 °C/decade, respectively. The average annual, spring, autumn, and winter precipitations exhibited inconspicuously increasing by 9.09, 8.62, 1.53, and 1.47 mm/decade, respectively, but the summer precipitation decreased by 1.5 mm/decade (Li *et al.* 2011).

It shows that different scales yield different trends in different climatic regions (Partal 2010). The purpose and significance of the study are to determine evolutions of meteorological factors, such as precipitation and temperature, in the Daqing River Basin from 1980 to 2015 and discuss the trends, changes, and periodicity. The results provide valuable references for the assessment of the effects of climate change and the management of the ecological environment.

MATERIALS AND METHODOLOGY

Materials

Study area

The Daqing River Basin is situated in the middle of the Haihe River Basin, located at 113°39′E~117°34′E, 38°10′N~40°02′N. It extends from the Taihang Mountains in the west to the Bohai Bay in the east, and bordering the Yongding River in the north and Ziya River in the south. The Daqing River flows through the Shanxi, Hebei, Beijing, and Tianjin provinces. The Xiong'an New Area is situated at the hinterland of the Daqing River Basin. The basin is a temperate monsoon climate with four distinct seasons and an annual precipitation of 500–700 mm. The annual average temperature is 8–10 °C, which is lower in the east and higher in the west. The study area is shown in Figure 1.

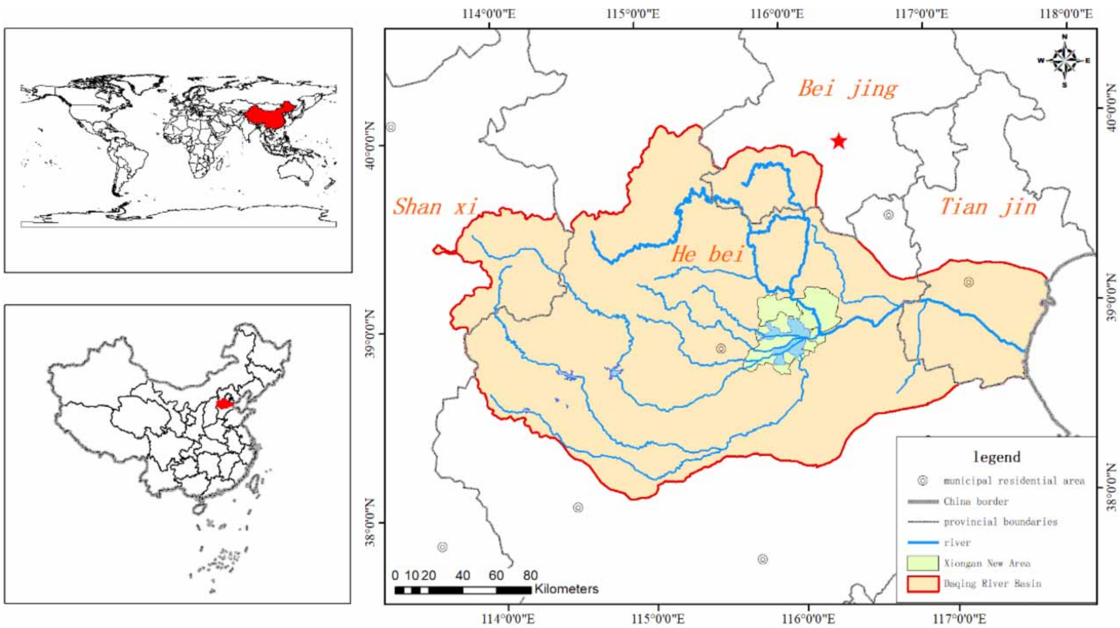

Figure 1 | Location of the Daqing River Basin.

Data acquisition

Taking the continuity of the series into account, this study is conducted with the daily-scale temperature and precipitation data of 40 meteorological stations in the Daqing River Basin from 1980 to 2015 provided by the National Meteorological Information Center. There are 43 national meteorological stations in the Daqing River Basin, but 3 of them miss some data. Therefore, the daily precipitation and temperature data of 40 stations are selected in this study. 93% of stations are chosen to ensure the reliability of the results. The distribution of meteorological stations is shown in Figure 2.

Methodology

Anomaly accumulation method

The anomaly accumulation is a method to judge the change trend directly from the curve. For the hydrological variable Yi with sample length n, the anomaly accumulation value S_k at a certain time is expressed as follows: (Jiang *et al.* 2020):

$$S_k = \sum_{i=1}^{k} (Yi - \bar{Y}), k = 1, 2, \ldots, n \quad (1)$$

where S_k is the anomaly accumulation value in the K year, Yi is the observation value in i year, $\bar{Y}$ is the average value of observation series, n is the length of observation series.

If S_k fluctuates around the value of zero, which indicates that there is homogeneity in time series. Then the standard deviation D_y is used to correct the scale of S_k.

$$D_y = \sqrt{\frac{\sum_{i=1}^{k} (Yi - \bar{Y})^2}{n}} \quad (2)$$

$$S_k^* = \frac{S_k}{D_y} \quad (3)$$

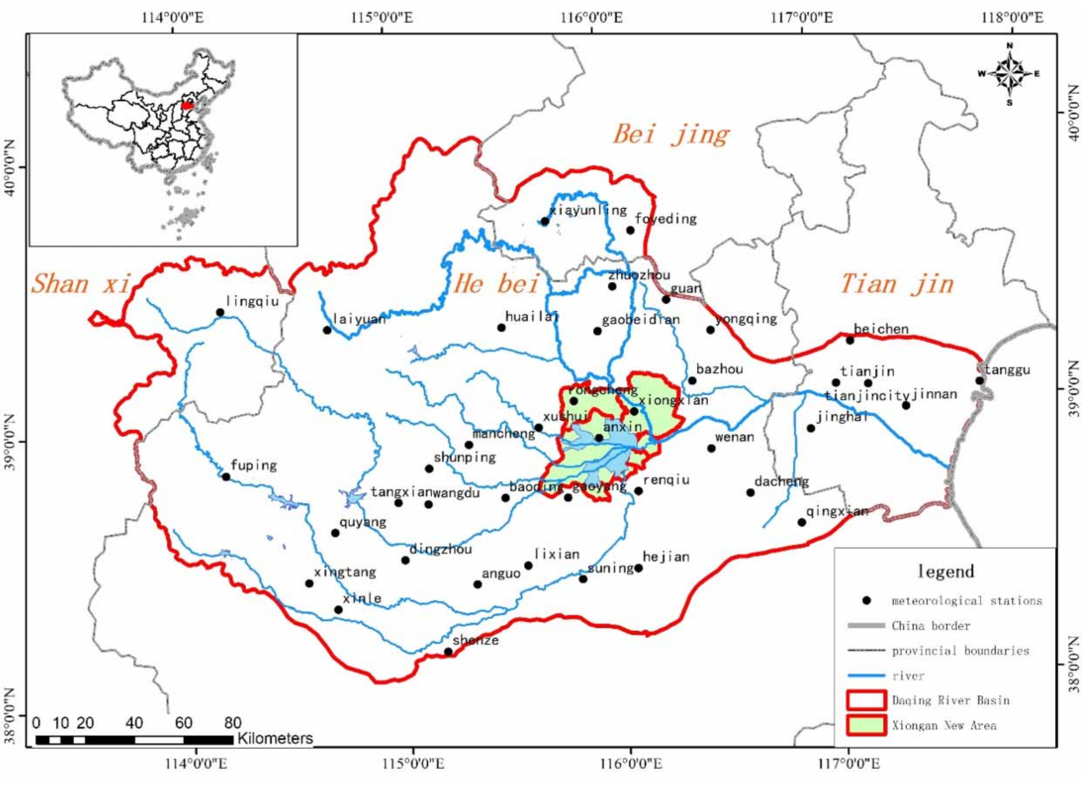

Figure 2 | Distribution of meteorological stations.

The homogeneity test statistic Q is the ratio of the maximum absolute value of S_k^* to $\sqrt{n}$.

$$Q = \frac{\max_{1 \le k \le n} |S_k^*|}{\sqrt{n}} \tag{4}$$

If the statistic Q exceeds the critical value, it means that the series is not homogeneous. Table 1 shows the critical values of Q at different confidence levels.

The core of this method is that when the data continues to exceed the average value, the anomaly accumulation value increases, and the curve shows an upward trend, otherwise, it shows a downward trend. According to the fluctuation of the curve, we can judge the long-term evolution trend of the time series.

Mann–Kendall method

Various statistical methods applied to test trends in hydrological series can be sorted to parametric and nonparametric methods (Dahmen & Hall 1990; Chen *et al.* 2007). Mann–Kendall test is the most common nonparametric test of time series trends (Mann 1945; Kendall 1990). It is recommended by the World Meteorological Organization as an effective means to evaluate whether the trend of hydrological and meteorological series is significant or not, and has been widely used to test the significance of temperature, precipitation, and runoff trends (Tabari & Talaee 2011; Wang *et al.* 2015). The Mann–Kendall test equations are as follows (Hamed 2009; Araghi *et al.* 2015; Güçlü 2018; Jiang *et al.* 2020):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(x_j - x_k) \tag{5}$$

$$\mathrm{sgn}(x_j - x_k) = \begin{cases} 1, & x_j - x_k > 0 \\ 0, & x_j - x_k = 0 \\ -1, & x_j - x_k < 0 \end{cases} \tag{6}$$

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)}{18} \tag{7}$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}}, & S < 0 \end{cases}. \tag{8}$$

where n is the number of samples, t is the extent of all ties (equal values), and x_j and x_k are the sample time series.

A positive statistical Z value indicates that the variable increases, whereas a negative value implies a decline. When $|Z| > Z_{1-\frac{\alpha}{2}}$, the variable has a notable upward or downward trend at the significant level α. The critical value $\pm Z_{1-\frac{\alpha}{2}}$ can be obtained from the literature.

When the Mann–Kendall is used to detect the mutation of a sequence, one rank is constructed, where rank S_k is the cumulative number of values at time i, which is greater than that at time j.

$$S_k = \sum_{i=1}^{k} r_i \qquad (k = 2, 3, \ldots n) \tag{9}$$

$$r_i = \begin{cases} 1 & (x_i > x_j) \\ 0 & (x_i \le x_j) \end{cases} \quad (j = 1, 2, \ldots i) \tag{10}$$

Definition of statistical variables:

$$UF_K = \frac{[s_k - E(S_k)]}{\sqrt{\mathrm{Var}(S_k)}} \qquad (k = 1, 2, \ldots n) \tag{11}$$

$$E(S_k) = \frac{n(n-1)}{4} \tag{12}$$

$$\mathrm{Var}(S_k) = \frac{n(n-1)(2n+5)}{72} \tag{13}$$

Table 1 | Critical values of statistic Q at different confidence levels

	statistic Q		
n	**99%**	**95%**	**90%**
10	1.05	1.14	1.29
20	1.10	1.22	1.42
30	1.12	1.24	1.46
40	1.13	1.26	1.50
50	1.14	1.27	1.52
100	1.17	1.29	1.55
∞	1.22	1.39	1.63

The parameter UF_K is the standardized normal distribution. Given the significance level α, if $|UF_K| > U_{\alpha/2}$, the sequence notably changes. Subsequently, the time series x is arranged in reverse order and computed according to the following equation:

$$\begin{cases} UB_K = -UF_K \\ k = n+1-k \end{cases} \quad (k = 1, 2, \ldots, n) \tag{14}$$

Based on the statistical sequence UF_K and UB_K, the change of the time series x and abrupt change point and area can be determined. If UF_K is above 0, the sequence has an upward trend; if it is below 0, the sequence has a downward trend. If the critical straight line is exceeded, the trend is significant. If there is an intersection between UF_K and UB_K between the critical lines, the time corresponding to the intersection is the time at which the abrupt change starts.

Rescaled range analysis (R/S analysis)

The R/S analysis method is also widely used in testing the hydrological series trend. The Hurst index ($0 < H < 1$), for different H, means that the sequence has different trends. When H is 0.5, the sequence is absolutely independent, that is, it is a random process. When $0 < H < 0.5$, it means that the future trend is opposite to that of the past (i.e., anti-persistent). The smaller H is, the stronger is the anti-persistence. When $H > 0.5$, it means that the future trend is identical to that of the past (i.e., persistent). The greater H is, the stronger is the persistence (Wang *et al.* 2002).

Wavelet analysis

Wavelet analysis is an efficient tool to study the multi-scale, non-stationary signals of time series (Hua & Hong 2012). Its development started with the processing of geophysical seismic signals by Morlet and Grossmann (Grossmann & Morlet 1984).

The wavelet transformation can be used to extend time series to the frequency domain to identify a local intermittent period. Wavelet analysis also reveals local time and frequency information when the time series is unstable. The continuous wavelet transform can be realized by scaling and translation with a parent wavelet function φ (Kang & Lin 2007; Nalley *et al.* 2012; Eunhyung & Sanghyun 2019):

$$\varphi_{a,b(t)} = |a|^{-\frac{1}{2}} \varphi\left(\frac{t-b}{a}\right) \quad (a, b \in R), \tag{15}$$

where a is the parameter of scale, b is the parameter of position, and t is the time. For any signal $f(t)$, the wavelet transformation is realized by the convolution of a wavelet scaling and translation set:

$$W_f(a, b) = |a|^{-\frac{1}{2}} \int_R f(t)\varphi * \left(\frac{t-b}{a}\right) dt, \tag{16}$$

where $*$ represents the conjugation and $W_f(a, b)$ denotes the wavelet coefficients. Therefore, the concept of frequency is replaced by the scale on a given scale, which describes the variation of a signal $f(t)$.

The wavelet variance is widely used to obtain the main period of the time series. It is the square of the wavelet transform coefficient that integrates b in the time-domain and can be expressed as follows:

$$\mathrm{Var(a)} = \int_{-\infty}^{+\infty} |W_f(a, b)|^2 db \tag{17}$$

The choice of the wavelet function hinges on the specific signal. The Morlet wavelet function is often used in the fields of climate and hydrology. Its definition is as follows:

$$\varphi_t = \pi^{-\frac{1}{2}} e^{iw_0 t} e^{-\frac{t^2}{2}}, \tag{18}$$

where w_0 is the dimensionless frequency. When $w_0 = 6$, the wavelet scale and Fourier period are equal. The wavelet spectrum can be used to detect the significance of the period through the spectral density over a range of time-scales; it can be calculated as follows (Araghi *et al.* 2016):

$$E_a = \frac{1}{N} \sum_{h=1}^{N} |W_f(a, b)|^2, \tag{19}$$

where N is the data length.

RESULTS

Characteristics of precipitation evolution

Precipitation homogeneity

The precipitation of the Daqing River Basin from 1980 to 2015 is analyzed using anomaly accumulation to determine if it is uniform. The cumulative value of precipitation is shown in Figure 3. The calculated Q value is 0.319126, and it is less than the critical value, which is 1.12 (99% confidence level). The precipitation is thus uniform.

Precipitation trend

A curve is drawn based on the annual average precipitation of the basin from 1980 to 2015. The linear regression equation and five-year moving average curve are fitted, and the rate of change is calculated (Figure 4). The Figure 4 shows an insignificant upward trend for the precipitation. Meanwhile, in the light of the Mann–Kendall test for precipitation, the Z value is 1.3123. It passes the significance test with 80% confidence, that is, Z value (1.3123) is greater than p value (1.28). But it fails to pass the significance test with 90% confidence, that is, Z value (1.3123) is less than p value (1.64). Because the

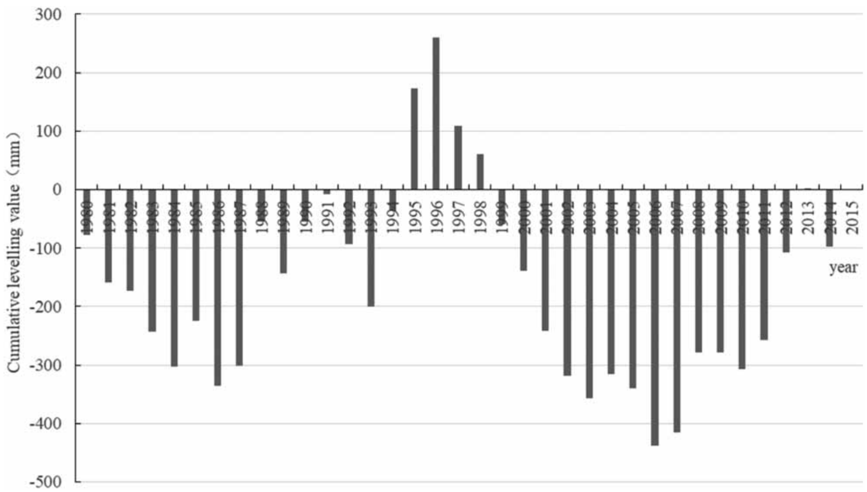

Figure 3 | Cumulative value from 1980 to 2015.

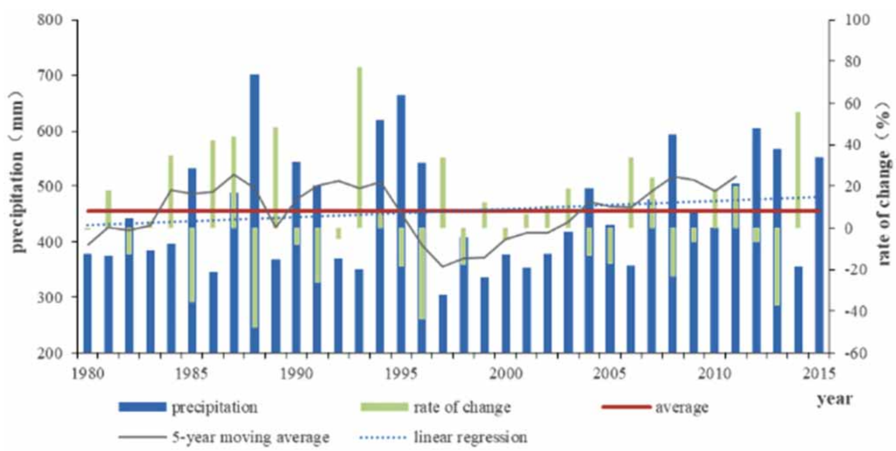

Figure 4 | Analysis of the precipitation trend.

value is above zero, there is an upward trend. By analyzing the change rate of precipitation in the past 36 years, it can be concluded that the average annual precipitation sometimes increases and sometimes decreases in the basin, and the overall trend is increasing. The precipitation fluctuated greatly from 1980 to 1995, and became stable after 1995, but it showed obvious fluctuation trend in recent years. Based on the R/S analysis and calculation, as shown in Figure 5. The regression equation of R/S is as follows:

$$\frac{R(x)}{S(x)} = 0.8517x^{0.3974} \tag{20}$$

The Hurst index is 0.3974. When $0 < H < 0.5$, the sequence has a long-term correlation, indicating anti-sustainability, that is, the overall changes of hydrometeorological elements in the future are opposite to those of the past.

The slip average method, Mann–Kendall test and R/S analysis are employed to analyze the precipitation trend. The results show that the precipitation increased from 1980 to 2015 but may decline in the future in the Daqing River Basin.

Abrupt change of precipitation

Mann–Kendall mutation test is mainly composed of UF, UB and critical line. The test method is: if the intersection of UF and UB curves occurs, and the intersection point is between the critical lines, then the corresponding time of the intersection point is the start time of mutation. So, the Mann-Kendall mutation test is used to analyze the abrupt change of long-term precipitation observation data in the Daqing River Basin, and the M-K statistic curve (Figure 6) is obtained. The statistical value of given significance level ($\alpha = 0.05$), that is, ± 1.96 is represented by the grey line. UF and UB curves can meet in many places. It can be seen from the figure that there are several very obvious intersections in the critical line of ± 1.96 in the period of 1982–1992 in the Daqing River Basin, indicating that there is no significant change in this time series. However, after 1992, the UF and UB curves intersected in 2007 and between the critical values ($\pm$ 1.96). This means that the precipitation suddenly changed in 2007.

Precipitation period

Real part and modulus square of the precipitation. The contour map of the real part of the wavelet coefficients expresses the periodic changes of the series over a range of timescales and its distribution in the time-domain and thus can be applied to determine the future trend. A positive real part of the wavelet coefficients represents a high flow period (solid lines in Figure 7), that is, the wet season. When it is negative, it represents a low flow period (dotted lines), that is, the dry season. Generally speaking, three

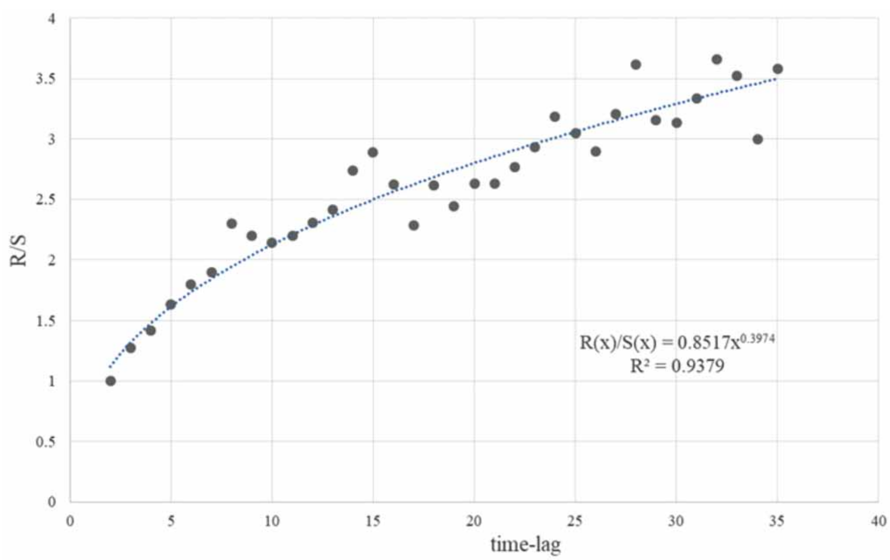

Figure 5 | Fitting of the R/S analysis.

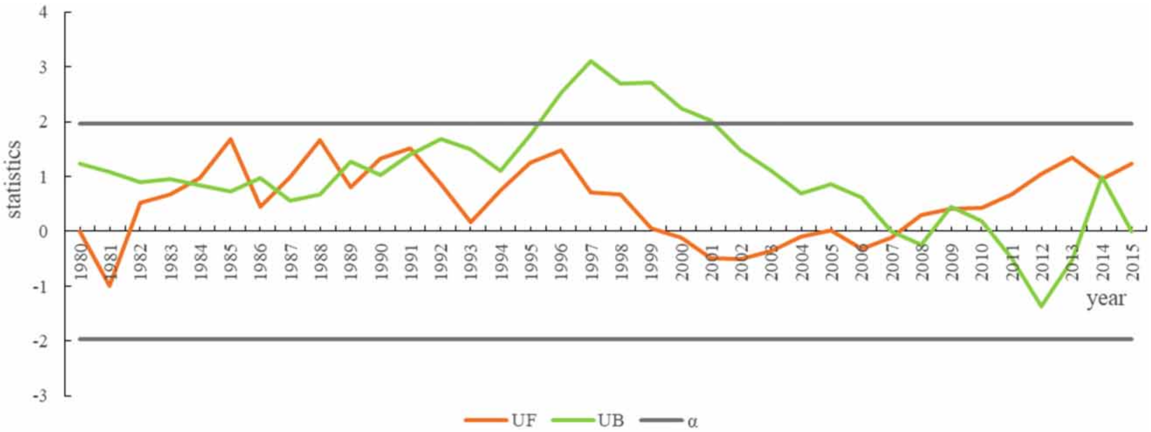

Figure 6 | UF and UB curves.

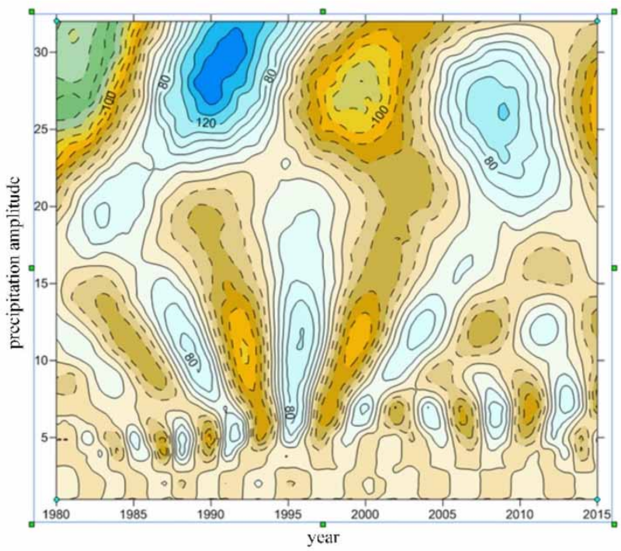

Figure 7 | Contour map of the real part.

types of periodic changes occur from 1980 to 2015 in the basin, that is, the 22–32-, 8–16-, and 3–7-year time scales, respectively. On the 22–32- and 8–16-year time scales, there are two and four quasi-periodic oscillations of dry and wet alternation. At the same time, the periodic changes of the above-mentioned two scales are very stable and global in the whole analysis period, while the periodic changes on the 3–10-year scale are relatively stable after 1995.

The modulus square of the wavelet coefficients corresponds to the wavelet energy spectrum, which can be used to acquire the vibrational energy of different periods. The energy on the 23–32-year scale is the most powerful and this period is the most noteworthy. However, the periodic change is local (before 2000s) based on Figure 8. Although the energy on the 10–15-year scale is feeble, a periodic distribution is notable, almost holding the whole research time domain (from 1983 to 2015).

Variance of precipitation. The map of wavelet variance expresses the distribution of the wave energy on a year scale and can be applied to judge the main period of precipitation evolution. The variance map of the precipitation in the basin shows four notable peaks (Figure 9), which correspond to the 28-, 12-, 7-, and 5-year time scales, respectively,

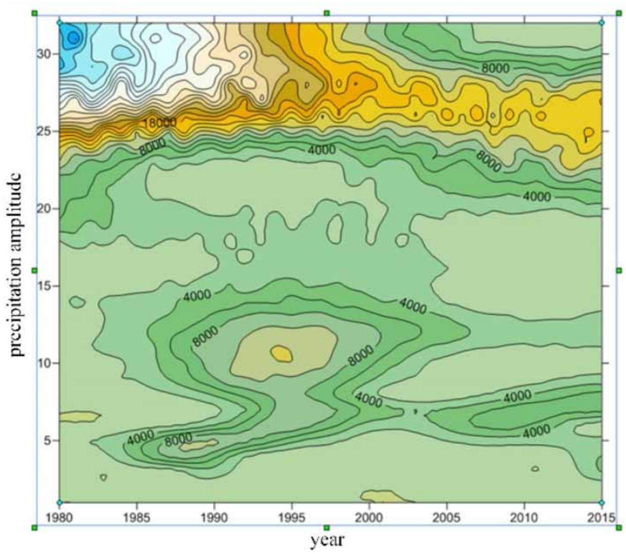

Figure 8 | Contour map of modulus square.

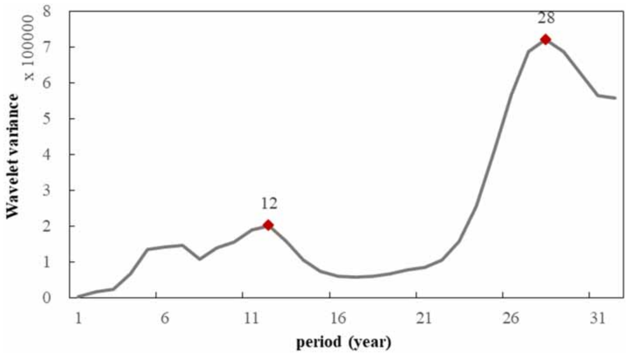

Figure 9 | Wavelet variance of the precipitation.

among them, the peaks of 28- and 12- year time scales are more obvious. The maximum peak matches the time scale of 28 years, indicating that the periodic 28-year oscillation is the most powerful, which is the first main period of precipitation change in the basin. The time scale of 12 years matches the second peak, which is the second period of precipitation change. The third and fourth peaks correspond to 7 and 5 years, respectively, which are the third and fourth periods of precipitation change, respectively. This shows that the undulations of the above-mentioned four periods control the evolution of precipitation in the whole time-domain.

Trend of the main period. Based on the trend of the main period shown in Figure 10, the average period and characteristics of the variation on different time scales are analyzed. On the 28 years scale, the average period of precipitation change in the basin is ∼20 years (1980–2000 and 2000–2020), with two cycles of wet and dry change. On the 12-year scale, the average period is ∼7.5 years (1983–1990, 1991–1999, 2000–2007 and 2008–2015), which includes four cycles of wet and dry change.

Characteristics of temperature evolution

Temperature homogeneity

The temperature in the Daqing River Basin is analyzed to determine whether it was uniform or not from 1980 to 2015. The cumulative value is shown in Figure 11. The Q value is 0.320163, and it is less than the critical value, which is 1.12 (99% confidence level), such that the temperature is uniform.

Temperature trend

The annual average value and change rate of temperature is drawn (Figure 12). The temperature has a significant upward trend. Meanwhile, based on the Mann–Kendall test for temperature, the Z value is 3.0919 and passes the significance test with 99% confidence. This means that we have 99% confidence in the significant trend of the temperature. A significant upward trend can be observed because Z is greater than zero. Through the analysis of the change rate of temperature, it can be seen that except for the large inter-annual changes during 1995–1997, the other years change little. Subsequently, the regression equation of R/S is as follows:

$$\frac{R(x)}{S(x)} = 0.8114x^{0.5418} \tag{21}$$

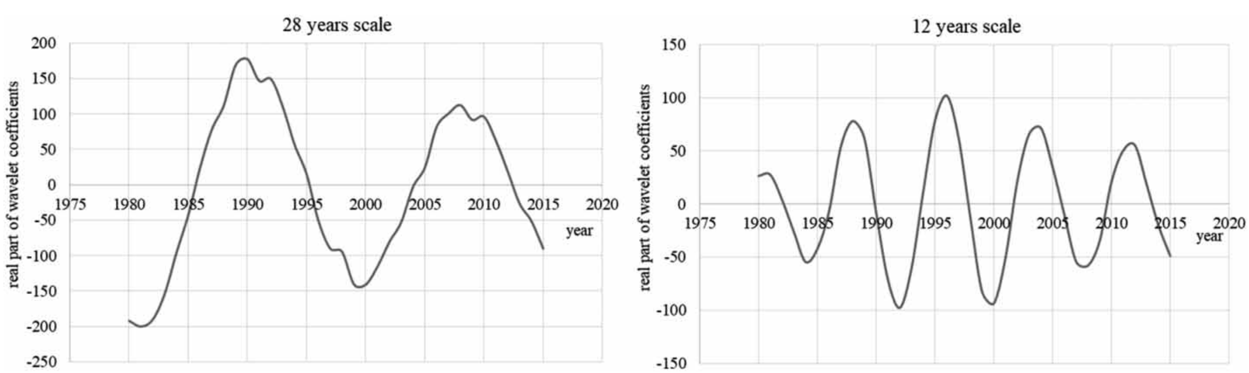

Figure 10 | Main period trends over 28 and 12 years.

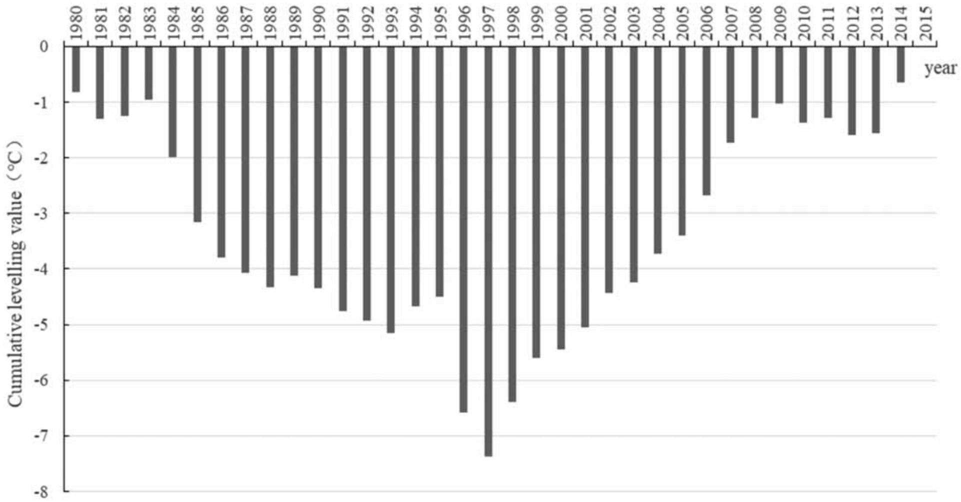

Figure 11 | Cumulative temperature value from 1980 to 2015.

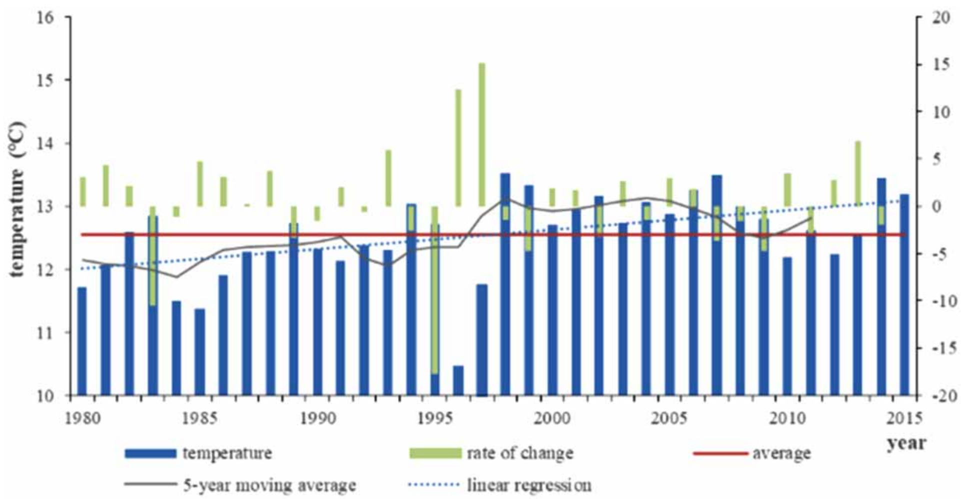

Figure 12 | Analysis of the temperature trend.

The Hurst index is 0.5418 (Figure 13), indicating that the sequence has a long-term correlation, which implies sustainability, that is, the overall change in the temperature in the future is consistent with that of the past. The slip average method, Mann–Kendall test, and R/S analysis are employed to analyze the temperature trend. The results indicate that the temperature significantly increased from 1980 to 2015 and will continue to rise in the future in the Daqing River Basin.

Abrupt change of temperature

On the basis of the Mann–Kendall mutation test, the intersection of UF and UB appeared in 1992, there is and only one intersection point, as shown in Figure 14. It is between the critical value (±1.96), indicating that the temperature suddenly changed in 1992.

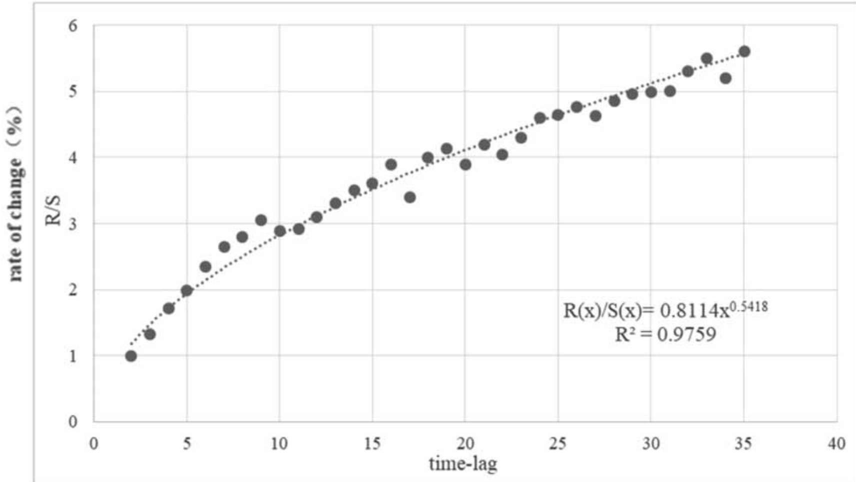

Figure 13 | R/S analysis result.

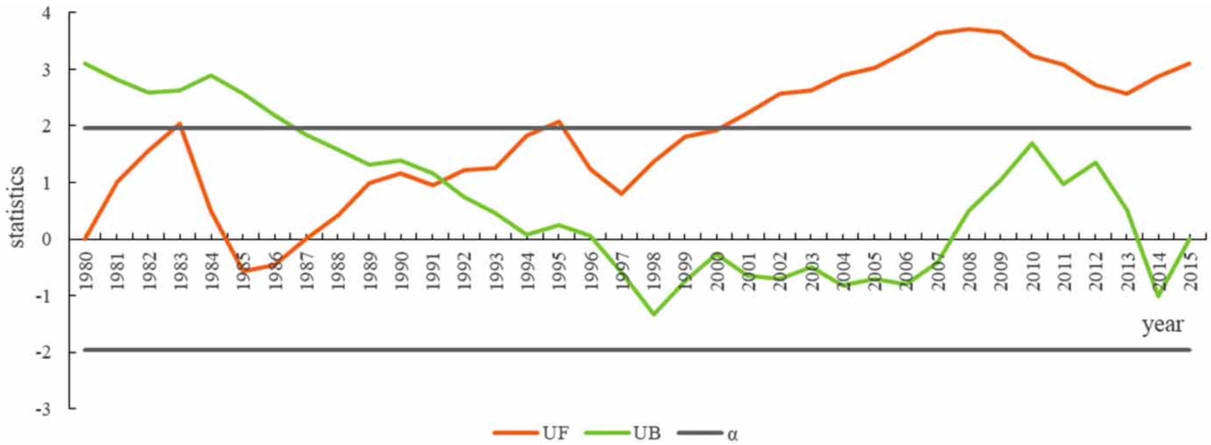

Figure 14 | UF and UB curves.

Temperature period

Real part and module square of the temperature. The map of the real part represents the distributions of different characteristics on different time scales. The solid line represents a positive wavelet transform coefficient, indicating that the temperature is higher. The dotted line represents a negative wavelet transform coefficient, indicating that the temperature is lower. Based on the analysis, there are three types of periodic changes of the annual average temperature, that is, the 5–10-, 14–20-, and 25–32-year time scales. On the 25–32- and 14–20-year time scales, two and three quasi-periodic oscillations of alternating dry and wet periods can be observed, respectively. The periodic changes of the above-mentioned two scales are very stable and occur globally, while the temperature frequently alternate on the 5–10-year scale (Figures 15 and 16).

Temperature variance. Figure 17 shows three notable peaks, which correspond to the 28-, 18-, and 8-year time scales, among them, the peaks of 28- and 18- year time scales are more obvious. The peak value matches the 28-year time scale, showing that the periodic oscillation of 28–year scale is the most powerful, which is the first main period of temperature change in the basin. The 18-year time scale matches the second peak, which is the second period of

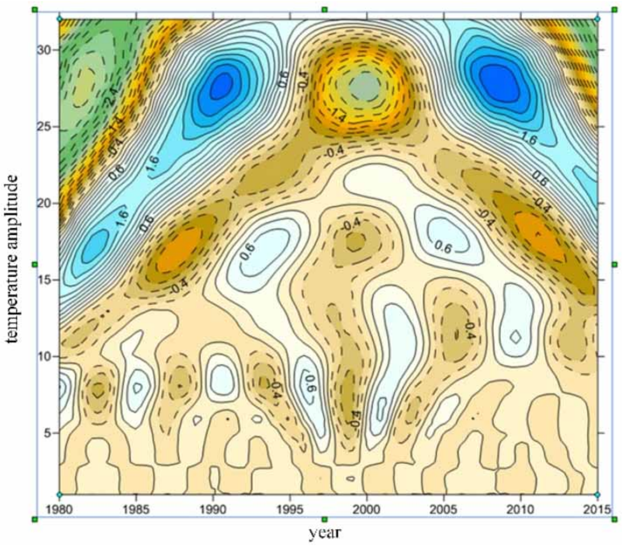

Figure 15 | Contour map of real part.

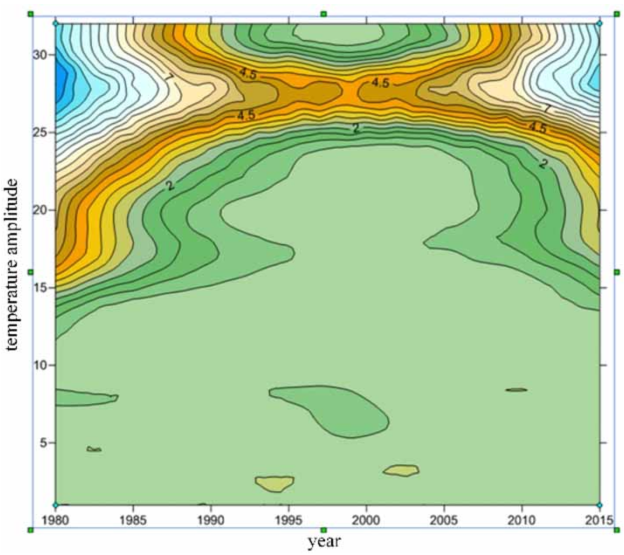

Figure 16 | Contour map of modulus square.

temperature change, and the 8-year scale matches the third peak, which is the third period. This indicates that the undulations of the above-mentioned three periods dominate the variation in the temperature in the whole time domain.

Trend of the main period. Based on the trends of the main period shown in Figure 18, the average cycle and cold–warm alternation of the temperature on different time scales are analyzed. On the 28- year scale, the average change period of the temperature in the basin is ~17.5 years (1982–2000 and 2001–2018), with two cycles of cold–warm alternation. On the 18-year scale, the average change period of the temperature is ~12 years (1981–1993, 1994–2005, and 2006–2017), with three cycles of cold–warm alternation.

DISCUSSION

Based on research on the characteristics of temperature, precipitation, runoff, and their mutual response, we compared with Mu *et al.*'s analysis on the evolution characteristics of water cycle impacting factors in the Daqing River Watershed (Mu *et al.* 2017). Their conclusions are as follows, (1) from 1970 to 2011, the annual precipitation in the Daqing River Basin showed an insignificant 'decrease-increase-decrease-increase' trend, while the average annual temperature showed a significant increase trend. (2) There was no abrupt change in the annual precipitation, and the annual average temperature changed suddenly in 1991. (3) The evolution cycle of annual precipitation and annual average temperature is 22 and 28 years, respectively. These are basically consistent with our research conclusions.

At the same time, Gao *et al.* believed that the annual average temperature increased in the Baiyangdian Basin and continued to rise after 1988. The increase in the temperature in spring and winter contribute most to the rising temperature. The change in the precipitation was relatively complex; it fluctuated and overall decreased. The precipitation in summer decreased the most (Gao *et al.* 2017). Guo *et al.* studied the temperature and precipitation from 1981 to 2008 in the Haihe Basin, the temperature increased significantly throughout the whole basin, and the trends ranged from 0.03 to 0.05 K/yr in the plain and from 0.06 to 0.12 K/yr in the mountain regions, respectively. The precipitation decreased in most parts except in the high mountain regions, where precipitation increased at a rate between 1 mm/yr and 5 mm/yr. However, both the decrease and increase trends are shown to be insignificant (Guo & Shen 2015). Our results regarding the temperature are in accordance with the results of the study of Gao *et al.* and Guo *et al.*, indicating an upward trend. However, we

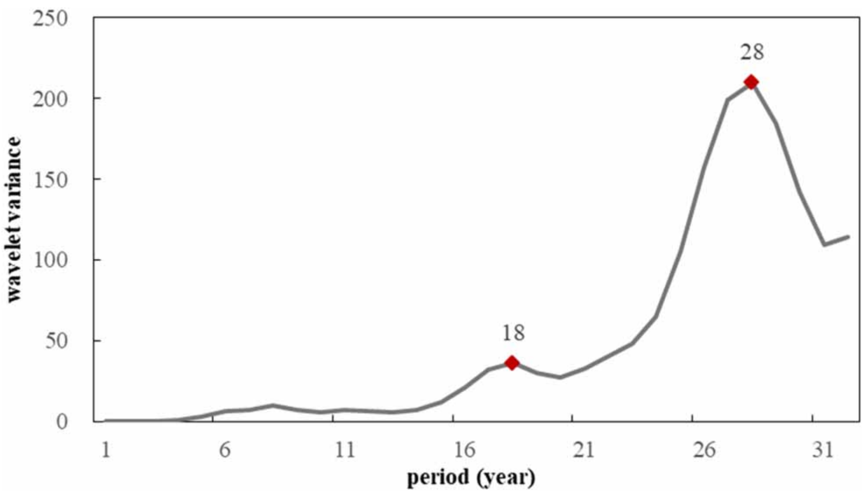

Figure 17 | Wavelet variance of the temperature.

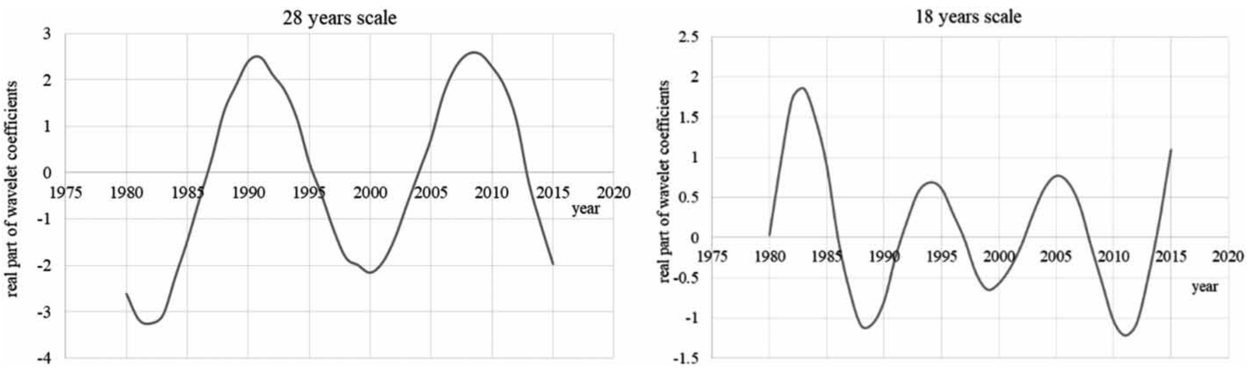

Figure 18 | Main period trends over 28 and 18 years.

obtain different results for the precipitation. The reason is the selected study period, which is different. The time range in this paper is 1980–2015, while it is 1957–2012 in Gao *et al.*'s and 1981–2008 in Guo *et al.*'s study. Because of the abundant precipitation before the 1980s, they observed a declining precipitation trend.

CONCLUSIONS

The evolution of meteorological factors, including precipitation and temperature, were analyzed in this paper based on trend, abrupt change, and periodicity analyses during 1980–2015 in the Daqing River Basin, North China. The annual precipitation shows an upward trend and sudden change in 2007, which may indicate a future downward trend. During the evolution of the precipitation, three types of periodic changes occur on the 22–32-, 8–16-, and 3–7-year time scales, respectively, with 28 years representing the first main period. This may be related to the affected by the monsoon climate, atmospheric circulation, solar movement, and greenhouse gases on precipitation in this area, so that there are large differences in time and space. The annual average temperature shows a notable upward trend. A sudden change occurs in 1992. Subsequently, the temperature notably rises and most likely will continue to increase in the future. There are three types of periodic changes of the annual average temperature on the 25–32-, 14–20-, and 5–10-year time scales, respectively, and 28 years represents the first main period. In conclusion, the climate of the Daqing River Basin gradually changes to a humid and hot climate.

In summary, the significant increases in the temperature and precipitation represent the main trend, which intensifies the development of humid and hot climate in the Daqing River Basin. First, the trends of precipitation and temperature in the region are consistent, indicating that the interannual change in the temperature is positively related to the precipitation. Secondly, based on the wavelet analysis, it can be concluded that there is a nested structure on multi-year scales of temperature and precipitation, which shows that the mutual response of the two parameters is prominent. The analysis of history is to better predict the future and actively respond to the various climate changes. These results provide useful information for the climate change assessment and the water resource management. In future research, the runoff data will be collected at hydrological stations to study the trends and periodicity of the region. More detailed research will be carried out on seasonal or even monthly scales.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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