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Wavelet analysis of the complex precipitation series in the Northern Jiansanjiang Administration of the Heilongjiang land reclamation, China

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ABSTRACT

Due to interference from natural factors and the intensity of human activities, the complex characteristics of the regional precipitation process have become increasingly evident, which creates a challenge for the rational development and utilisation of precipitation resources. In this perspective of complexity diagnosis, the multi-timescale variation characteristics of precipitation were analysed in the Northern Jiansanjiang Administration of Heilongjiang land reclamation, China, by the wavelet analysis method. The results showed that the most complex precipitation series was at Qinglongshan Farm. There are five significant main periods of approximately 2, 3, 4, 9 and 12 years in the seasonal and annual precipitation of Qinglongshan Farm; these periodic variation characteristics are almost identical to the periods of the El Niño-Southern Oscillation phenomena and sunspot activity, which illustrates that climate change has a major influence on the local precipitation variation characteristics. At the same time, precipitation in summer and autumn has similar periods and a similar variation trend to the annual precipitation at Qinglongshan Farm, which indicates that the local annual precipitation variation characteristics are mainly affected by summer and autumn precipitation variation. In contrast with the harmonic analysis method based on Fourier transform, wavelet analysis has a significant advantage in terms of accurately identifying the main cycle of the hydrological time series.
Key words | complexity, period, precipitation, trend, wavelet transform

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INTRODUCTION

As an important component of the hydrologic cycle, precipitation is the key factor influencing regional agricultural production, drought and flood disasters, and is an important supply source of surface water and groundwater. Precipitation has vital significance for disaster prevention and mitigation, restoration and sustainable utilisation of groundwater resources and agricultural sustainable development; understanding precipitation requires the study of the variation characteristics of multi-timescales of regional precipitation series and analysis of the changing regularity of droughts and floods. In recent years, the complexity of regional precipitation series has become increasingly apparent because of the increase in human interference. The traditional precipitation time series analysis method often ignores the complexity of the series itself and leads to a full demonstration of the difficulty and poor practicability results of the structure of the precipitation series. In this context, it is necessary to perform complex measurements for obtaining the regional multiple precipitation monitoring data series, screening the most complex series as a sample series, and revealing the overall regional precipitation characteristics.

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The traditional methods for determining the variation characteristics of multi-timescale precipitation mainly include Fourier analysis (Almeida *et al.* 2004; Prokop & Walanus 2003), spectral analysis (such as singular spectrum, power spectrum, etc.) (Maheras *et al.* 1992; Moten 1993; Gajić-Čapka 1994; Piervitali & Colacino 2001; Türkeş *et al.* 2002) and empirical mode decomposition-maximum entropy spectral analysis (Sang *et al.* 2012). These methods do not have time-frequency localisation properties and lack mathematical rigour in the diagnosis of an abrupt point (Liu *et al.* 2009), so the variation characteristics of multi-timescales of precipitation cannot be fully reflected. However, wavelet analysis, which was developed in the early 1980s, is the ideal approach of functional analysis, Fourier analysis, spline analysis, harmonic analysis and numerical analysis (Zou & Mo 1999), as it has a time-frequency multi-resolution function and rigorous analysis on abrupt points in mathematics; in addition, wavelet analysis can show the fine structure of multi-timescales of precipitation series (Wei & Wu 2011), being currently widely applied in the field of hydrology and water resources.

Many scholars have used wavelet analysis to explore the variation characteristics of multi-timescales of regional precipitation series. Özger *et al.* (2010) used the continuous wavelet transform (CWT) to analyse the monthly precipitation series from 43 stations in Texas, in the United States, and the results showed the annual period played an important role in the characterisation of dry spells. Zhan *et al.* (2011) adopted the Poyang Lake Basin daily precipitation observations of China from 1959 to 2008 and used the Mexican hat wavelet analysis to reveal annual precipitation that had a quasi-period of 20 years and rainfall in flood season that has a quasi-period of 6 years. Jury & Melice (2000) used the CWT to analyse monthly precipitation data from 1872 to 1999 in Durban, South Africa; the results showed that the monthly precipitation had 1- and 2.3–4-year periods, which accounted for 33% and 10% of rainfall variance, respectively. Subash *et al.* (2011) applied Morelet wavelet analysis and the power spectrum method to analyse the Central Northeast India monthly rainfall during June–September, the total rainfall during monsoon season and the annual rainfall from 1889 to 2008; the results showed that none of the precipitation series had obvious periodicity. Kim (2004) used the Mexican hat wavelet transform to analyse the spatio-temporal variation characteristics of five precipitation series from 1905 to 2001 in northern California; the results revealed that the spatial pattern of the precipitation field may have changed since 1945, and the dominant period was approximately 16 years.

Most of the studies regarding the multi-timescale variation characteristics of precipitation usually adopted the average of the multi-station as the sample series. Meanwhile, although some researchers adopted the wavelet analysis method to extract the primary cycle of precipitation, the results lacked representativeness and accuracy because they ignored the significance test process. Therefore, the aim of this article is to screen the most complex seasonal precipitation series as the sample series combining the theory of entropy, fractal and Lempel-Ziv complexity (LZC), and reveal the multi-timescale variation characteristics of seasonal rainfall and annual precipitation series in the Northern Jiansanjiang Administration of Heilongjiang land reclamation in China using the Morelet wavelet analysis method.

The rest of the paper is organised as follows. The 'Materials and methods' section briefly introduces the general information about the study area, describes the basic data used in this study, and presents the methods employed in this study. Then the results obtained with real rainfall series data are presented and discussed. Conclusions are given in the final section.

MATERIALS AND METHODS

Study area

The Jiansanjiang Administration of Heilongjiang land reclamation is located in the hinterland of the Sanjiang plain of Heilongjiang province in China, which is at the junction of Fujin and Tongjiang, Fuyuan and Raohe. This area is located at north latitude 46°49′42″–48°13′58″ and east longitude 132°31′26″–134°22′26″, with a total area of districts of 12,300 km^2 and 682,000 hm^2 of cultivated land (Liu *et al.* 2012). Jiansanjiang Administration includes 14 farms, of which four farms are in the northern area: Qinglongshan, Qindeli, Nongjiang and Yalvhe (Figure 1). The total area of the land and cultivated land are 2,900.81 km^2 and 1,470 km^2, respectively. The area includes the Xunhuangyu Provincial Nature Reserve of Qingdeli and the three Administration Nature Reserves of Qinglong rivers, Nongjiang and

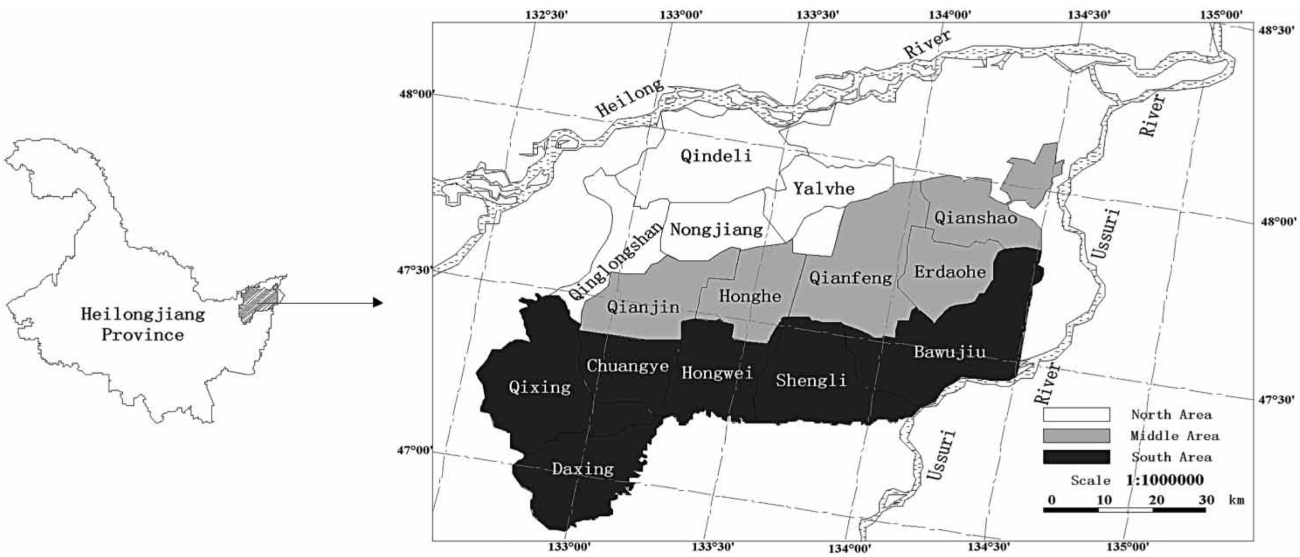

Figure 1 | The location of the Northern Jiansanjiang Administration of Heilongjiang land reclamation in China.

Yalvhe. The rate of mechanisation and the production of commodity grain is high, with a main growing of rice, corn, soybeans and wheat. In the 1990s, there was an attempt to grow rice in the area, such that the area of rice was increasing year by year, reaching 105,000 hm^2 in 2009, and accounting for 71.4% of the arable land. Under the influence of various natural factors (e.g., the solar activity period, the EI Niño-Southern Oscillation (ENSO) phenomenon, terrain, geographic position, etc.) and human activities (e.g., afforestation, turning wet land into farmland, construction of water conservancy projects, etc.), the variation of area inter-annual precipitation is large, and the intra-annual distribution is uneven, leading to the complex characteristics becoming increasingly apparent. Against this background, it is necessary to explore and reveal the mechanism of the precipitation's complex behaviours and analyse the precipitation changing law for drought and flood, which can provide guidance for local agricultural production.

Data description

Monthly precipitation and annual precipitation data for 13 farms were collected from the weather station of the Jiansanjiang Administration of the Heilongjiang land reclamation (the farm of Nongjiang has no data). The spring (March to May), summer (June to August), autumn (September to November) and winter (December to the next February) precipitation of each farm were calculated; the changing curves of the seasonal precipitation series for Qinglongshan, Qindeli and Yalvhe are shown in Figure 2. The changing curves and fitting curves of the seasonal and annual precipitation series of Qinglongshan, Qindeli and Yalvhe are shown in Figure 3.

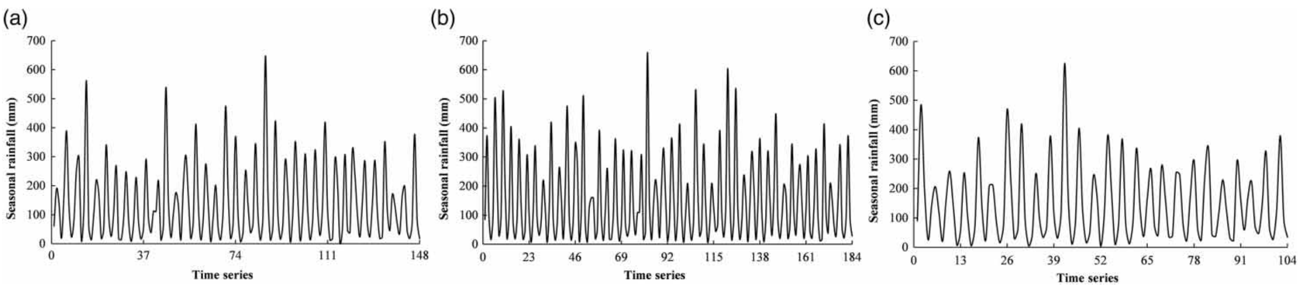

Figure 2 | Changing curves of the seasonal precipitation series of each farm in the Northern Jiansanjiang Administration. (a) Qinglongshan, (b) Qindeli, (c) Yalvhe.

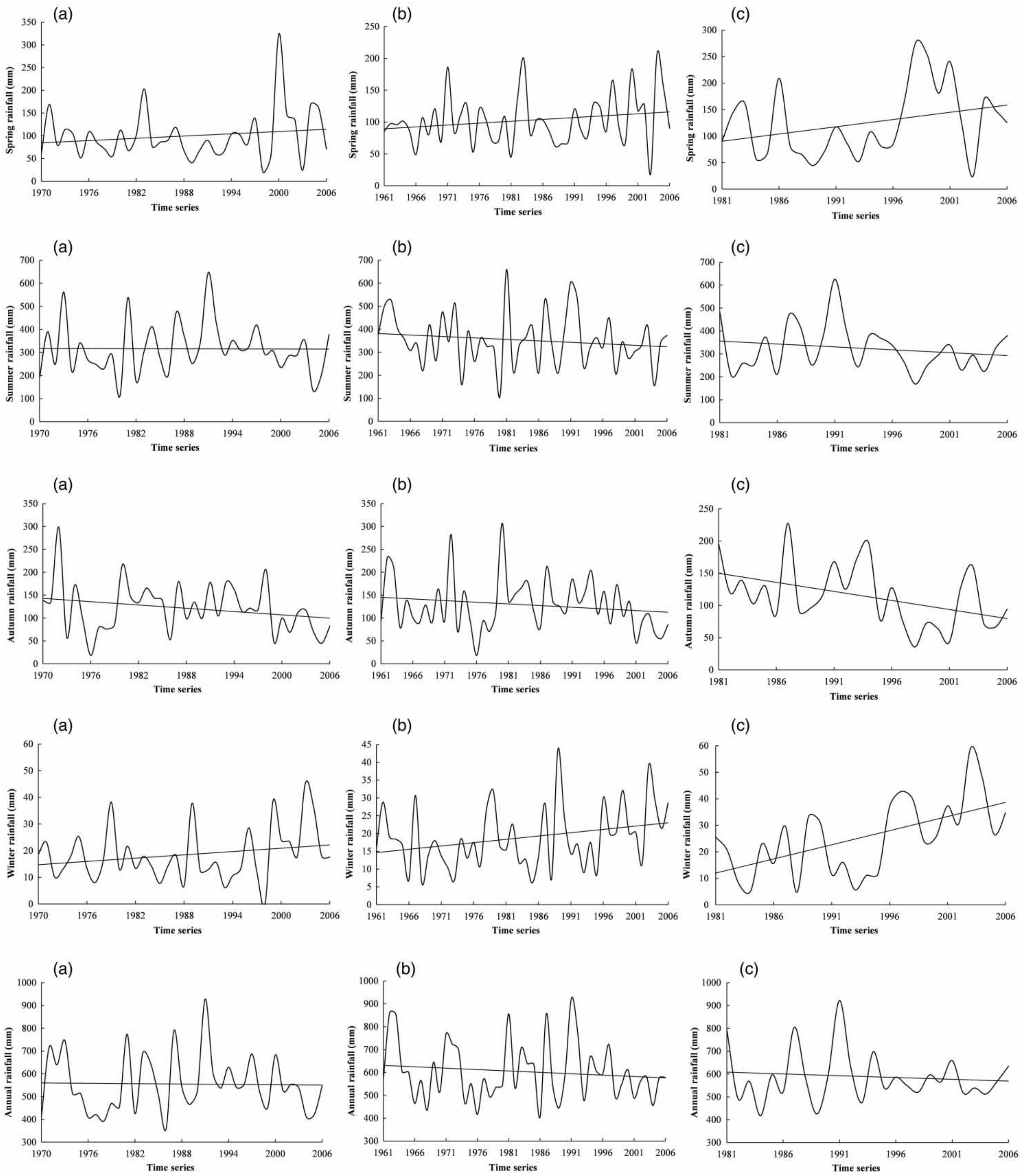

Figure 3 | Curve patterns of the annual and seasonal precipitation series of each farm in the Northern Jiansanjiang Administration: (a) Qinglongshan; (b) Qindeli; (c) Yalvhe.

Figure 2 shows that the seasonal precipitation series of each farm has an obvious characteristic seasonal period variation of decreasing in the spring and winter and increasing in the summer and autumn in the Northern Jiansanjiang Administration. At the same time, although those series have obvious seasonal period characteristics, the change in their mean and variance is not smooth, belonging to the non-stationary time series. Thus, the dynamic changes include random and non-linear complexity characteristics. From Figure 3, the seasonal and annual precipitation series of each farm are both non-stationary time series in the Northern Jiansanjiang Administration, with similar variation characteristics. The spring and winter precipitation has a gradually increasing trend, whereas the summer and autumn precipitation has a gradually decreasing trend. The summer and autumn precipitation is significantly higher than that of the two seasons of spring and winter, resulting in a superimposed effect of the annual precipitation gradually reducing.

Methodology

The methods of measuring the hydrological series' complexity

The methods for measuring hydrological series complexity include wavelet entropy (WE) (He *et al.* 2011), approximate entropy (ApEn) (Pincus 1991), LZC (Zhao *et al.* 2011), fractal theory based on resealed range analysis (R/S) (Matos *et al.* 2004; Wang *et al.* 2005), fractal theory based on discrete wavelet transform (DWT) and CWT (Wang *et al.* 2005), etc. The basic principles of the above-mentioned complexity measurement methods can be found in the relevant literature.

The wavelet function

The wavelet function refers to the turbulence characteristics, which are functions with limited energy and zero average, $\int_{-\infty}^{+\infty} \psi(t)dt = 0$ (Chen & Zhu 2007). Wavelet analysis always adopts one of the following: Haar wavelet, Morlet wavelet, Meyer wavelet, Mexican hat wavelet, Daubechies wavelet, etc. (Provazník 2001). Here, we use the Morlet wavelet, which has a good locality of the time and frequency domains; the Morlet wavelet is (Li 1999; Lardies & Gouttebroze 2002; Wang *et al.* 2005; Werner *et al.* 2007):

$$\psi(t) = e^{ict}e^{-t^2/2} \tag{1}$$

where c is constant, and i is imaginary.

The Morlet wavelet is obtained after a periodic function goes through Gaussian function smoothing; thus, its scale factor a has a one-to-one relationship with the period of the Fourier transform: $T = \left[4\pi/\left(c + \sqrt{2 + c^2}\right)\right] \times a$. When the constant c is 6.2, $T = 1.00057a \approx a$. Thus, the Morlet wavelet can be used for period analysis.

The wavelet transform

Wavelet transform is the core of wavelet analysis. For one hydrological time series $x(t)$, if $x(t)$ is a quadratically integrable function, $x(t) \in L^2(R)$ (mean finite energy), for a given wavelet function, the CWT of $x(t)$ is (Gross *et al.* 1995; Provazník 2001; Wang *et al.* 2005; Werner *et al.* 2007; Zhu & Meng 2010):

$$W_x(a, b) = \langle x(t), \psi_{a,b}(t)\rangle = |a|^{-\frac{1}{2}}\int_{-\infty}^{+\infty} x(t)\overline{\psi}\left(\frac{t-b}{a}\right)dt \tag{2}$$

where W_x (a, b) is the Wavelet transform coefficient, $\langle,\rangle$ is the inner product, $\psi_{a,b}(t)$ is a family of functions that is called the mother wavelet, which is formed by dilation and shift of $\psi(t)$, $\overline{\psi}(t)$ is a complex conjugate function of $\psi(t)$, a is a scale dilation factor, and b is a time shift factor.

The hydrological time series are mostly discrete in actual application. For example, $x(k\Delta t)$ ($k = 1, 2, \ldots, n$, Δt is the time interval of sampling); thus, the discrete formation of Equation (2) can be expressed as (Wang *et al.* 2005; Liu & Ma 2007):

$$W_x(a, b) = |a|^{-\frac{1}{2}}\Delta t\sum_{k=1}^{n} x(k\Delta t)\overline{\psi}\left(\frac{k\Delta t - b}{a}\right) \tag{3}$$

$W_x(a, b)$ can simultaneously reflect the characteristics of the time domain parameter b and the frequency domain parameter a, as well as its filter output of time series $x(t)$ through the unit-pulse response. The smaller the a value, the lower the frequency domain resolution, but the higher the time domain resolution and vice versa. Thus, the

Wavelet transform is a time and frequency localised analysis method with a fixed window but a changeable shape. According to the change of $W_x(a, b)$ with a and b, we can choose b as the x-axis and a as the y-axis, and then draw a two-dimensional isoline map about $W_x(a, b)$, which is called the wavelet transform coefficient map. Through analysing the wavelet transform coefficient map, we can obtain the wavelet change characteristics of a hydrological time series in the wavelet transform domain; accordingly we can reveal the multi-timescale variation characteristics and jump characteristics of the hydrological time series.

The wavelet variance and its significance test

The wavelet variance is the integral of the entire squares of $W_x(a, b)$ about a in the time domain. For a discrete hydrological time series, wavelet variance can be calculated with the following equation (Wang *et al.* 2005; Bjerkås 2006; Liu & Ma 2007; Yu *et al.* 2012).

$$Var(a) = \frac{1}{n}\sum_{b=1}^{n} |W_x(a,b)|^2 \tag{4}$$

where n is the swatch number, and $|W_x(a,b)|^2$ is the modulus square of the wavelet transform coefficient.

The variation course of wavelet variance going with scale 'a' is called the wavelet variance map. This map can reflect the fluctuation of various scales (namely periods) included in the hydrological time series and its change characteristics of intensity (energy magnitude) with the scales. Each peak value represents each notable period in the map. Thus, we can conveniently confirm the main timescales (namely the main periods) that exist in a time series through the wavelet variance map.

Whether the wavelet variance is significant can be determined by adopting the standard spectrum of red and white noise to test. The standard spectrum can use the following formula for judgement (Torrence & Compo 1998):

$$r_c = \frac{-1 + 1.645\sqrt{n-2}}{n-1} \tag{5}$$

If the lag-1 autocorrelation coefficient in the original series $r(1) > r_c$, red noise is taken; otherwise, making $r(1) = 0$, white noise is taken. The specific texting formula is as follows (Torrence & Compo 1998):

$$P_a = \frac{1 - r(1)^2}{1 + r(1)^2 - 2r(1)\cos\left(\frac{2\pi\Delta t}{1.033a}\right)} \tag{6}$$

where P_a is the red or white noise standard spectrum (when $r(1)$ is equal to zero, P_a is the white noise standard spectrum); Δt is the original series of the time intervals.

$$P = \sigma^2 P_a \frac{\chi_v^2}{v} \tag{7}$$

where P is the wavelet power spectrum; σ^2 is the original series variance; χ_v^2 is the distribution of values of χ^2, with significance level $\alpha = 0.05$ (freedom being v). Among them, $v = 2\sqrt{1 + \left(\frac{n\Delta t}{2.32a}\right)^2}$.

If $Var(a) > P$, then the relevant period of that wavelet variance is significant.

RESULTS AND DISCUSSION

Complexity analysis of precipitation series

To adequately consider the mutual effect of the complicated dynamic change of each farm's precipitation, the above six different methods were adopted to measure the complexity of the seasonal precipitation series of each farm in the Jiansanjiang Administration; Table 1 shows the sorted results (only northern area sorted results are listed). The range analysis of fractal theory is relatively sensitive to the series length, belonging to the biased estimation, with a slightly poor stability (Rakhshandehroo *et al.* 2009); however, the stability of the Wavelet fractal theory is higher (Wang *et al.* 2005), with the others in the middle. To give full play to the advantages of various types of complexity measurement methods (Pan *et al.* 2011, 2012), based on the above analysis, we determined the weight of various complexity levels, see Table 1.

The complexity sorted results (①–⑭) of each farm's seasonal precipitation series based on six different methods

Table 1 | Calculation of the integrated complexity index of each farm's seasonal precipitation series in the Northern Jiansanjiang Administration

							D							
									Wavelet estimation					
	WE **(0.16)**		***ApEn*** **(0.16)**		***LZC*** **(0.16)**		***R/S*** **(0.10)**		***DWT*** **(0.21)**		***CWT*** **(0.21)**			
Farm	**sorting**	**value**	**sorting**	**value**	**sorting**	**value**	**sorting**	**value**	**sorting**	**value**	**sorting**	**value**	C_{Ij}	**Sorted complexity**
Qinglongshan	①	14	③	12	②	13	⑬	2	⑨	6	⑨	6	8.96	④
Qindeli	⑤	10	④	11	⑫	3	⑤	10	⑭	1	⑭	1	5.26	⑫
Yalvhe	⑦	8	⑨	6	⑤	10	②	13	⑫	3	⑩	5	6.82	⑩

Figures in brackets give the weight of the precipitation series complexity measure; *D* is the fractal dimension.

were assigned corresponding scores; thus, the formula of integrated complexity index of seasonal precipitation series can be obtained:

$$C_{Ij} = \sum_{i=1}^{6} s_{ij} w_i \tag{8}$$

where C_{Ij} is the integrated complexity index of the seasonal precipitation series of the jth ($j = 1, 2, \ldots 14$) farm, and s_{ij} is the complexity sorted value of the seasonal precipitation series of the jth farm belonging to the ith method. From Table 1, the sorted complexity of the seasonal precipitation series of each farm in the Northern Jiansanjiang Administration is as follows: Qinglongshan Farm > Qindeli Farm > Yalvhe Farm. The C_{Ij} value of Qinglongshan Farm is the largest, which indicates this farm has more influencing factors for seasonal precipitation, and the complexity of the precipitation system dynamics structure is stronger. So, as represented by the Qinglongshan Farm for the North sub-area of Jiansanjiang Administration, the seasonal and annual precipitation measured series data are analysed with multi-timescales to understand the detailed structure and variation trend of different timescales.

The time-frequency characteristic analysis of complex precipitation series

To conveniently handle the measured precipitation series, data ($n = 37$) of the four seasons of spring, summer, autumn, winter and the annual precipitation (March to the next February) from 1970 to 2006 in Qinglongshan Farm were analysed with anomaly (centralisation). The wavelet transform coefficients $W_f\,(a, b)$ of the precipitation anomaly series $f(k\Delta t)$ ($k = 1, 2, \ldots 37$; $\Delta t = 1$) in Qinglongshan Farm were calculated using Equation (3).

The modulus square isoline map (see Figure 4) and the real part isoline map (see Figure 5) of the wavelet transform coefficient $W_f(a, b)$ of each precipitation anomaly series in Qinglongshan Farm were drawn according to the aforementioned method, and the precipitation anomaly series time-frequency characteristics were analysed, taking spring as an example.

Figure 4(a) shows that the signal energy distribution strength of different timescales of the spring precipitation anomaly series, in which the signal energy change over timescales of 3 to 8 years is the strongest, are found to mainly occur in the periods from 1980 to 1988 and 1994 to 2006, with an oscillation at the centres in 1983 and 2000. The signal energy of timescales of 13 to 24 years mainly occurs in the period from 1978 to 2006. The signal energy of timescales of 1 to 3 years mainly occur in the periods from 1970 to 1972, 1988 to 1990 and 1999 ~ 2004. The signal energy of the other cases has a lower amount of change.

Figure 5(a) shows the variation of different timescales of the spring precipitation anomaly series, and the changing point distribution and structure of the positive and negative phases; the timescales of 3 to 8 and 12 to 25 years are the most obvious, the positive and negative phase appear alternately, and the central timescales of the periods are approximately 4 years and 17 years, respectively. In addition, the timescales of 8 to 11 years also appear and the central timescale is approximately 9 years.

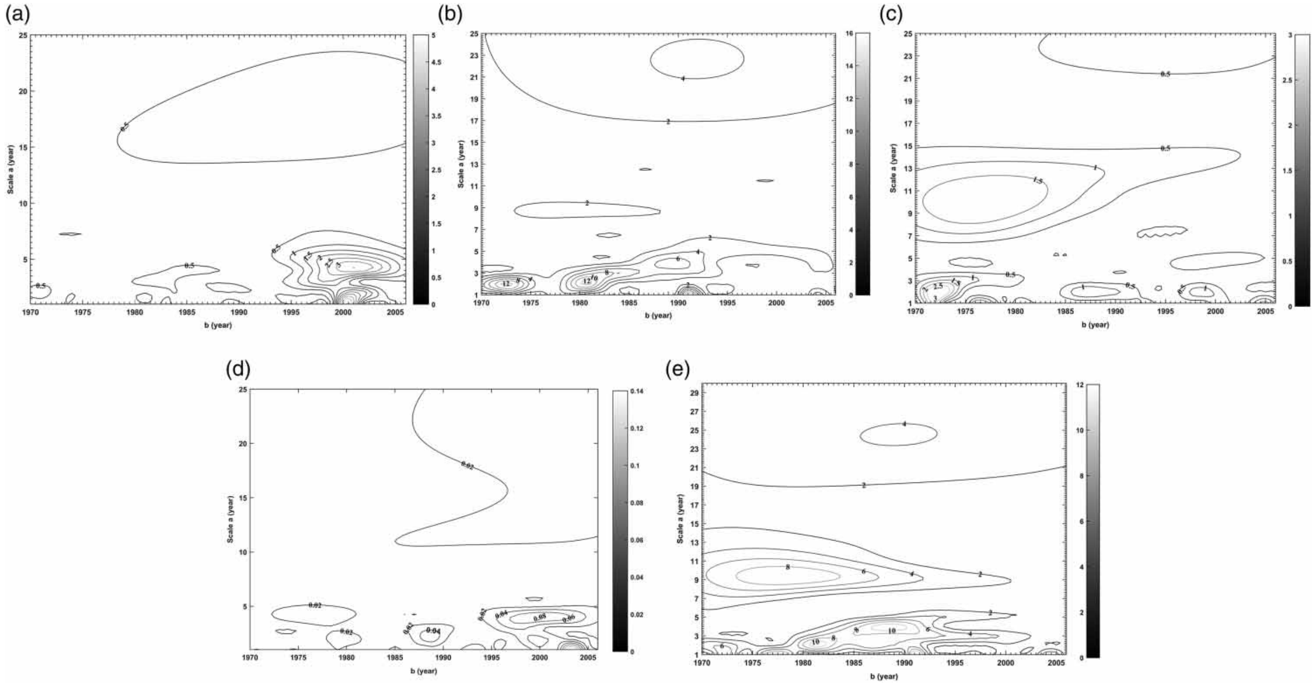

Figure 4 | Wavelet transform coefficient modulus square isolines of each rainfall anomaly series in Qinglongshan Farm: (a) Spring, $\times10^4$; (b) Summer, $\times10^4$; (c) Autumn, $\times10^4$; (d) Winter, $\times10^4$; (e) Annual, $\times10^4$.

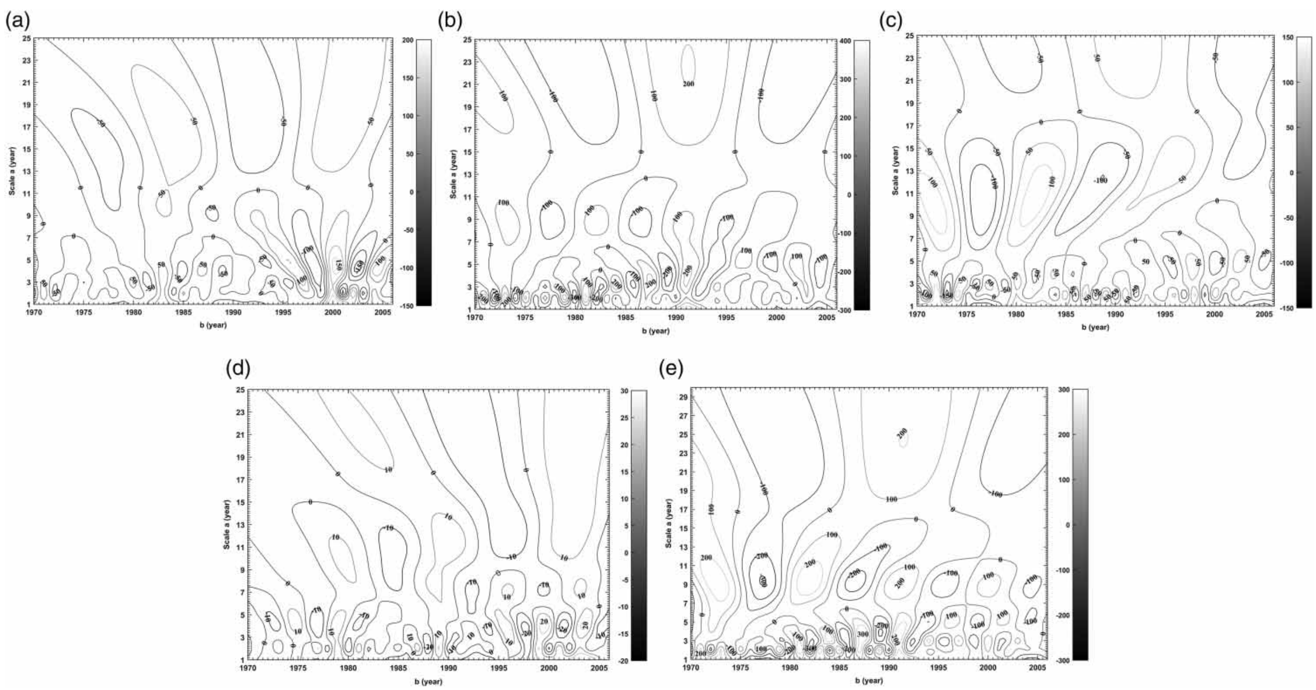

Figure 5 | Wavelet transform coefficient real part isolines of each rainfall anomaly series in Qinglongshan Farm: (a) Spring; (b) Summer; (c) Autumn; (d) Winter; (e) Annual.

The main period analysis of the complex precipitation series

Considering the wavelet transform coefficients under different scales, the wavelet variances were calculated using Equation (4), and the wavelet variance maps of each precipitation anomaly series in Qinglongshan Farm were drawn (see Figure 6); based on the maps, the main periods of the precipitation anomaly series were analysed, taking spring as an example.

From Figure 6(a), it can be observed that the main peaks of wavelet variances appear in scales $a = 4$, 9 and 17. For the scale of $a = 4$, the first peak value is the corresponding wavelet variance, which indicates that rectilinear oscillation is the strongest at approximately 4 years. This first peak value is the first main period, and the second and third main periods are 17 years and 9 years, respectively. To distinguish whether the above-mentioned main periods have statistical significance, it is necessary to perform a significance test.

After calculation, the first-order autocorrelation coefficient of the spring precipitation anomaly series in Qinglongshan Farm is $r(1) = -0.0380$. Next, r_c was calculated according to Equation (5), $r_c = \frac{-1 + 1.645\sqrt{37-2}}{37-1} = 0.2426 > r(1)$. Thus, the wavelet variances were tested using the white noise spectrum with Equations (6) and (7), and the 95% confidence level line was drawn (see Figure 6(a)). It can be observed that only the 4-year period exceeds the 95% confidence level line, i.e., the significant main period of the spring precipitation series is approximately 4 years in Qinglongshan Farm.

The significant main periods of the other precipitation anomaly series were recognised using the same method (see Table 2). The results reveal that the two seasons of summer and autumn precipitation series have similar main periods to the annual precipitation series in Qinglongshan Farm, i.e., the two seasons of summer and autumn precipitations have the same changing trend of a gradual reduction at Qinglongshan Farm from Table 2. Thus, the two seasons of summer and autumn precipitation commonly control the precipitation throughout the year. In Table 2, significant main periods of approximately 2, 3, and 4 years are consistent with the period in the range of 2 to 7 years of the ENSO (Tudhope *et al.* 2001; Moore 2008), and the significant main periods of 9 years and 11

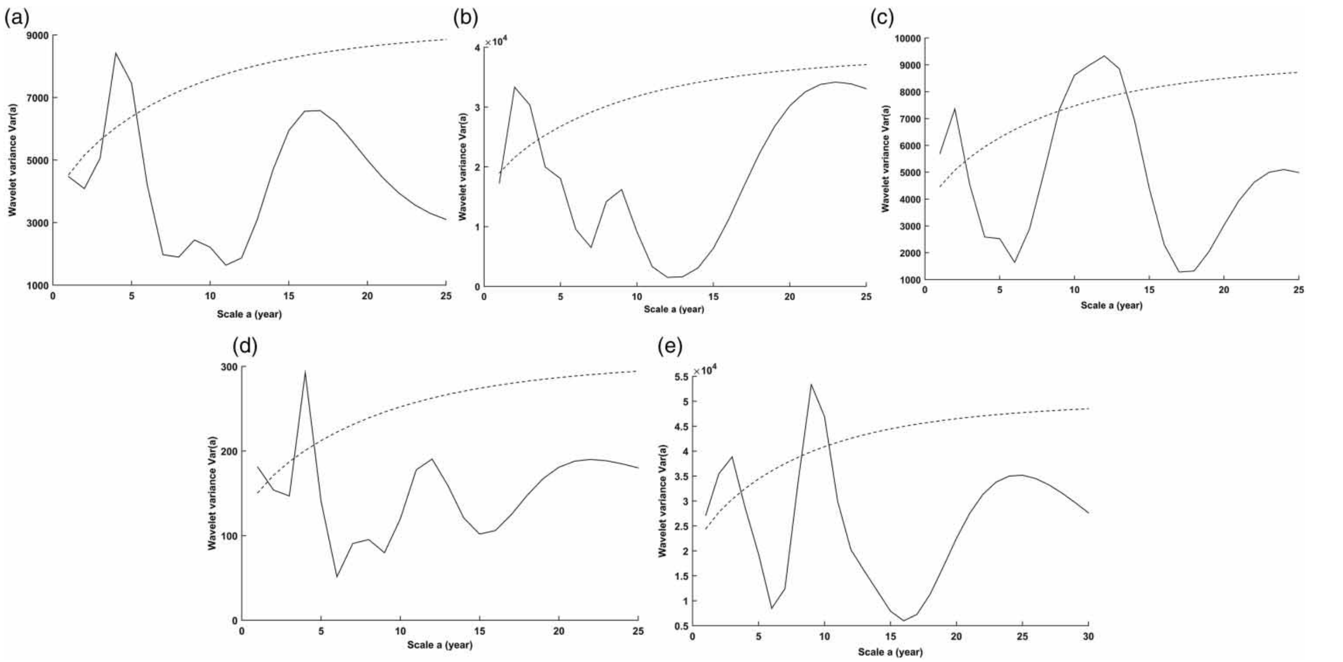

Figure 6 | Wavelet variance of each precipitation anomaly series in Qinglongshan Farm: (a) Spring; (b) Summer; (c) Autumn; (d) Winter; (e) Annual. The solid lines are wavelet variances and the dashed lines are the 95% confidence level.

Table 2 | Main periods of different precipitation series in Qinglongshan Farm

Precipitation series	Main periods	Significant main periods
Spring	4-year, 17-year, 9-year	4 years or so
Summer	2-year, 23-year, 9-year	2 years or so
Autumn	12-year, 2-year, 24-year	2 years or so, 12 years or so
Winter	4-year, 12-year, 22-year, 8-year	4 years or so
Year	9-year, 3-year, 25-year	3 years or so, 9 years or so

years are almost the same as the 11-year period of sunspot activity (Zolotova & Ponyavin 2006), which illustrates that ENSO is the main cause of the periodic variation characteristics of spring, summer and winter precipitation in Qinglongshan Farm, and the periodic variation characteristics of autumn and the annual precipitation are due to the dual influences of ENSO and sunspot activity.

The period ingredient of the precipitation series of spring, summer, autumn, winter and the year can be recognised using the harmonic analysis method based on the Fourier transform (Bu *et al.* 2012); the results are shown in Table 3. From Tables 2 and 3, we can see that the significant main period of the winter precipitation series is 4.1 years according to the harmonic analysis method based on Fourier transform; this period is the same as the 4-year period determined via the wavelet analysis method. The significant main periods of the annual precipitation series are 2.1 years and 9.3 years according to the method of harmonic analysis based on the Fourier transform; this is the same as the 3-year and 9-year periods recognised by the wavelet analysis method. The significant main period of the autumn precipitation series is 2.2 years according to the method of harmonic analysis based on the Fourier transform; this is the same as the 2-year period recognised by the wavelet analysis method. However, the significant main period of

Table 3 | Main periods of different precipitation series in Qinglongshan Farm based on harmonic analysis

Precipitation series	Spring	Summer	Autumn	Winter	Year
Significant main periods	–	–	2.2 year	4.1 year	2.1 year, 9.3 year

12 years cannot be recognised. In addition, the main period of the spring and summer precipitation series cannot be recognised in Qinglongshan Farm. These discrepancies may be due to the short length of the precipitation series. The above analysis shows that the wavelet analysis algorithm has some advantages in terms of analysing the multiple timescale change features of the hydrological time series. Meanwhile, the pattern of extracting the precipitation main period in this paper can remedy some of the disadvantages identified in some references (Jury & Melice 2000; Kim 2004; Özger *et al.* 2010), such as ignoring the significance test and the lack of strictness in extracting the main period.

Variation trends of different precipitation series and countermeasures for drought resistance and waterlogging control

To further analyse the changing drought and waterlogging fluctuation characteristics of the precipitation series in Qinglongshan Farm, taking the spring precipitation as an example, the timescale values a were fixed (separately taking $a = 4$, 9, and 17) in Figure 5(a), and the cutting lines parallel to the axis b were drawn. The points on the cutting line determine the vitiation process lines of the real part ($R[W_f(a, b)]$) of the wavelet transform coefficient $W_f(a, b)$ with time shift b (see Figure 7). The changing trend of smaller scales for 4 years and 9 years shows the spring precipitation was low in the period from approximately 2007 to 2008 in Qinglongshan Farm but higher after 2009. The changing trend of larger scales for 17 years shows the spring precipitation was low in the period of approximately 2007 to 2014 in Qinglongshan Farm but higher within the 8 years after 2015.

The changes in the drought and waterlogging processes of the rest of the precipitation series were analysed, and their variation trends were revealed (see Table 4). It can be observed that the trend of precipitation in summer and autumn is just the opposite of that in spring and winter under the condition of the smaller scales of 4 years and 9 years, demonstrating that summer and autumn precipitation dominates the annual precipitation changing trend at smaller scales. The exception is winter precipitation; the rest of the precipitation series has a

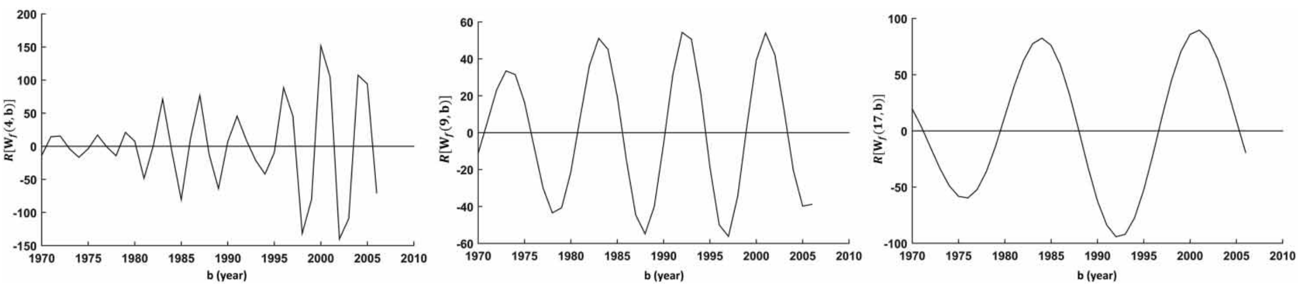

Figure 7 | The real part of the changing process of the spring precipitation anomaly series Morlet wavelet transform coefficient in Qinglongshan Farm for different timescales.

Table 4 | The changing trend of different precipitation series in Qinglongshan Farm

Precipitation series	The changing trend of smaller scales	The changing trend of larger scales
Spring	2007 to 2008 years or so, fewer periods; 2009 years later, more periods	2007 to 2014 years or so, fewer periods; 2015 to 2023 years, more periods
Summer	2007 years or so, more periods; 2012 years later, fewer periods	2007 to 2009 years or so, fewer periods; 2010 to 2021 years, more periods
Autumn	2007 years or so, more periods; 2011 years later, fewer periods	2007 to 2010 years or so, fewer periods; 2011 to 2022 years, more periods
Winter	2007 years or so, fewer periods; 2012 years later, more periods	2007 to 2008 years or so, more periods; 2009 to 2020 years, fewer periods
Year	2007 years or so, more periods; 2012 years later, fewer periods	2007 to 2010 years or so, fewer periods; 2011 to 2024 years, more periods

similar trend to the annual precipitation on the larger scale of 17 years, indicating that the local change trend of the annual precipitation is subject to the three seasons of spring, summer and autumn.

According to Table 4, the future key points of drought resistance and waterlogging control for the Northern Jiansanjiang Administration can be formulated (see Table 5). It can be observed that drought and flood disasters are frequent in the next 10 years in the Northern Jiansanjiang Administration. The following measures are recommended to improve the ability of local farmland to withstand natural disasters (see Table 6).

Table 5 | Focus on drought resistance and waterlogging control in the future of the Northern Jiansanjiang Administration

Time interval	Focus
2012 to 2014 years or so	Spring drought resistance
2015 to 2022 years or so	Spring drought resistance
2012 to 2020 years or so	Summer waterlogging resistance
2012 to 2021 years or so	Autumn waterlogging resistance
2012 to 2019 years or so	Winter drought resistance

CONCLUSIONS

This article used the complexity measures of WE, LZC, fractal theory and Morlet wavelet transform to analyse the variation characteristics of the precipitation series over multi-timescales in the Northern Jiansanjiang Administration. The following conclusions can be drawn from the study:

1. Qinglongshan Farm has the highest integrated complexity indices of the seasonal precipitation series, demonstrating that natural factors and human activities have the greatest influence on the local precipitation. Thus, taking the precipitation series of Qinglongshan Farm as the sample series of the Northern Jiansanjiang Administration can reflect the regional precipitation period change characteristics accurately and comprehensively, and the selected sample series and period analysis are highly representative.
2. The Qinglongshan Farm seasonal precipitation and annual precipitation series have significant main periods of 2 to 4 years, 9 years and 12 years, which indicate that the ENSO and sunspot activity are the main causes for the period variation characteristics. The result reveals the two seasons of

Table 6 | Measures for drought resistance and waterlogging control of the Northern Jiansanjiang Administration in the future

Drought resistant engineering measures	Drought resistant non-engineering measures	Waterlogging engineering measures	Waterlogging non-engineering measures
• Speed up the Linjiang irrigation district construction progress and improve the water supply ability	• Generalise drought resistant tillage measures, cultivation measures and chemical measures	• Construct the backbone drainage engineering	• Choose flood-drought resistant varieties or change paddy field to dryland
• Reduce water loss and improve irrigation assurance	• Select or develop local appropriate drought resistant varieties	• Build field supporting drainage engineering	• Change farming to wetland and lake
• Build a drought emergency water source engineering system	• Change paddy fields to drylands	• Strengthen the desilting for drains (river)	• Establish flood disaster assessment and disaster reduction decision support system
	• Establish the drought monitoring and early warning system	• Improve waterlogged drainage engineering standards	

summer and autumn precipitation series have a similar main period and change trend to those of the annual precipitation series in Qinglongshan Farm; thus, the two seasons of summer and autumn precipitation commonly control the precipitation throughout the year.

3. The harmonic analysis method based on Fourier transform can only recognise the 2.2-year period of precipitation in autumn, the 4.1-year period of precipitation in winter, and the 2.1-year and 9.3-year periods of annual precipitation, which confirms that the wavelet analysis is an excellent tool that can reveal the fine structure of the hydrological time series and extract the period accurately.
4. Agricultural production will continue under the threat of drought and flood disasters in the Northern Jiansanjiang Administration in the next 10 years. It is recommended that the local government should make a reasonable plan of disaster prevention and mitigation, adopting the appropriate measures to improve the ability of local farmland to withstand natural disasters.

In fact, the lack of precipitation monitoring data in Nongjiang Farm inevitably affects the complexity sorting results of each farm. Therefore, selecting a valid spatial interpolation method, such as Ordinary Kriging, Co-Kriging, Improved Inverse Distance Weighted, etc., to interpolate the precipitation series of Nongjiang Farm can amend the research results of the precipitation complexity in the Jiansanjiang Administration. This topic is worthy of further study in the future.

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