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Analysis of Temporal Evolution Characteristics of Annual Precipitation in the Yellow River Delta

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ABSTRACT

Precipitation is an important component in the climate system and plays a key role in water resources protection, drought and flood prevention. Innovation Trend Analysis (ITA) method, R/S method, maximum entropy spectrum analysis and wavelet analysis were used to study the evolution characteristics of the Yellow River Delta annual precipitation from 1954 to 2014. The results suggest that the precipitation series changed significantly and showed an overall downward trend, and may show an upward trend in the future, which is relatively strong. There are three-time scales of annual precipitation variation: 20-32a, 8-18a, and 3-6a. The quasi-27 year was the main oscillation period of the average annual precipitation in the Yellow River Delta, the secondary major period was 13 years, and the small-scale oscillation period was 5 years. Precipitation changed suddenly in 1980 and 2003. In contrast, there was no significant mutation point in 2002-2014.

INTRODUCTION

Precipitation is the main climate change factor that affects the distribution and function of a wetland and is one of the leading factors for the rational development of water resources and regional freshwater supply. Freshwater has become the key factor restricting the development of the Yellow River Delta. Therefore, it is necessary to study the characteristics and law of precipitation evolution, which can provide a theoretical and scientific basis for the sustainable development of the Yellow River Delta. At present, the study of precipitation evolution has become a public topic for many scholars at home and abroad. Common trend analysis methods include moving average method (Pei & Guo 2001), Mann Kendall rank correlation method (Mann 1945), cumulative horizon method (Ran et al. 2010), quadratic smoothing method (Li et al. 2018), R/S analysis method (Liu et al. 2019). Liebimnn & Marengo (2001) studied the relationship between seasonal rainfall characteristics and temperature changes in the Amazon. Galy-Lacaux et al. (2009) studied the long-term trend of precipitation chemical characteristics in rural areas of Banizoumbou. Sohoulande Djebou et al. (2014) and other scholars applied the entropy theory to study the relationship and its evolution characteristics between precipitation time and precipitation in the southwestern United States. Zhang et al. (2020) studied the historical trend of temperature, precipitation and runoff in the North China plateau basin by Mann Kendall. Zuo et al. (2019) analysed the precipitation characteristics in Tongzhou district of Beijing from 1966 to 2016 with Morlet wavelet transform. Ding et al. (2014) studied the temporal and spatial evolution of precipitation in a typical small watershed in the humid region of South China. Yang & Sun (2013) used the R/S method to analyze the runoff time series period. The above traditional methods only analysed the variation of sequence from one side of trend or mutation, but not from the whole (including cycle, trend and mutation, etc.) to judge whether the sequence has a mutation. According to the previous research results, this study adopts a new trend research method- ITA (Wu & Qian 2017, Huang et al. 2018). The ITA method has no limitations and is suitable for series-related, non-normal distribution, or short record lengths. It can identify the trend of low, medium and high value simply and clearly. Hurst coefficient can represent the variation of hydrological series as a whole from the perspective of time. R/S analysis method is usually used to analyze the time-series features and long-term memory process. The maximum entropy spectrum method overcomes the problems of data windowing and frequency resolution error. Wavelet analysis can carry out multi-scale refinement analysis of functions or signals. Therefore, this paper puts forward an analysis method to identify and test the variation and degree of variation of hydrological time series as a whole, which provides basic data support for agricultural production, water resource management and social and economic development of the Yellow River Delta.

MATERIALS AND METHODS

Method of Precipitation Trend Analysis

ITA method: ITA method (Wu et al. 2017, Huang & Qian 2018) is an innovative trend analysis method based on the linear comparison of the scattered points 1:1 (45°) on the cartesian coordinate system. It is divided into two equal parts according to the time series, and the sub-series are arranged in ascending order. The first sub-series is the X-axis, and the second sub-series is the Y-axis. If two subsequences are equal, indicating no trend, the points in the scatter plot fall on the 1:1 line. If these points fall above the 1:1 line, it indicates that the time series presents an increasing trend. On the contrary, there is a downward trend in the time series. At the same time, precipitation is divided into low, medium and high parts with 40% and 60% as the boundary according to the ascending sequence. ITA index D is used to characterize the trend, as shown in formula (1). When the range of value variation is small, but the influence of variation trend on production and life is too large to be ignored, the index value is not enough to clearly show the variation trend, then formula (2) can be referred to.

$$D = \frac{1}{n}\sum_{i=1}^{n}\frac{10\times(y_i - x_i)}{\bar{x}} \quad \ldots(1)$$

$$D = \frac{1}{n}\sum_{i=1}^{n}\frac{100\times(y_i - x_i)}{\bar{x}} \quad \ldots(2)$$

R/S analysis method: R/S analysis method was first proposed by Hurst (Hurst et al. 1965, Wallis & Matalas 1970, Rao & Bhattacharya 1999), a British hydrologist, and also known as the standard range analysis method. It was first used in hydrological research. In recent years, with the progress of science and technology, it has been widely used and developed in data analysis (Hjelmfelt et al. 1988, Tarboton et al. 1988, Zhang et al. 2005). Set time series $\{x(t)\}, t = 1,2,\cdots,n$. Where $\tau \geq 1$ and is an integer, when any value is taken:

Construct a mean number column:

$$x_t = \frac{1}{\tau}\sum_{i=1}^{\tau} x(t), \quad \tau = 1,2,\cdots,n \quad \ldots(3)$$

Cumulative dispersion:

$$x(t,\tau) = \sum_{k=1}^{t}[x(k) - x_\tau], \quad 1 \leq t \leq \tau \quad \ldots(4)$$

Range sequence:

$$R(t) = max\ x(t,\tau) - min(t,n) \quad \ldots(5)$$

Standard deviation:

$$s(t) = \sqrt{\frac{1}{\tau}\sum_{t=1}^{\tau}[x(t) - x_\tau]^2} \quad \ldots(6)$$

For the ratio: $(\tau)/S(\tau) = R/S$, if $R/S \propto \tau^H$, if , it can be said that sequence has Hurst phenomenon. H is the Hurst function. Judging the persistence and anti-sustainability of time series trends (Teverovsky et al. 1999, Huang et al. 2002) according to definitions. If $0 \leq H \leq 0.5$, it means that the time series is an anti-persistent or ergodic time series with a stronger mutation or variability than the random sequence, and the general trend of precipitation change is contrary to the past in terms of precipitation index. If $H = 0.5$, it means that the time series is a random swimming series, the observations are completely independent and the precipitation indicators change randomly in terms of precipitation index. If $0.5 < H < 1$, indicating that the time series is persistent or trend-enhancing, the overall trend of the change in precipitation in the future is the same as in the past

Precipitation Cycle Test Method

Maximum entropy spectrum analysis: The Burg recursive algorithm (Bassingthwaighte et al. 1994) is a commonly used maximum entropy spectrum analysis method. The algorithm is simple and the spectral resolution is relatively high. The specific steps are as follows:

Calculate the initial value

$$\varphi_i(0) = \frac{1}{N}\sum_{n-1}^{N}|x(n)|^2 \quad \ldots(7)$$

$$e_0(n) = b_0(n) = x(n) \quad \ldots(8)$$

Let $p = 1$, find the reflection coefficient

$$K_p = -\frac{2\sum_{k=p}^{n-1} e_{p-1}(n)\cdot b_{p-1}(n)}{\sum_{n=p}^{N}[e_{p-1}(n)^2 + b_{p-1}{}^2]} \quad \ldots(9)$$

$$a_{11} = K_1, \sigma_1{}^2 = (1 - |K_1|^2)\varphi_x(0)$$

Find $e_1(n)$, $b_1(n)$ from K_1 and the following formuls

$$e_p(n) = e_{p-1}(n) + K_p b_{p-1}(n-1) \quad \ldots(10)$$

$$b_p(n) = b_{p-1}(n-1) + K_p e_{p-1}(n) \quad \ldots(11)$$

Following the recursive relationship of Levinson of $a_{pk} = a_{p-1,k} + K_p a_{p-1,p-k}$ and $a_{pp} = K_p$, when $p = 2$, a_{11}, a_{22}, $\sigma_2{}^2$ are obtained.

Repeat the above process untilequals the required AR model order. Find all the AR model parameters a_{pk}, and then use the following formula to find the power spectral density.

$$P_{Burg(\omega)} = \frac{{\sigma_p}^2}{\left|1+\sum_{k=1}^{p} a_{pk} e^{-jw(k)}\right|} \quad \ldots(12)$$

Morlet wavelet: Morlet wavelet analysis has been extensively studied in the periodic variation of precipitation (Adamowski & Chan 2011, Chen et al. 2019). Morlet wavelet analysis has a phase difference of π/2 between the real part and the imaginary part of the complex function. It can reveal the various change periods hidden in the time series, reflect the trend of the reaction system at different time scales and predict the future development trend of the system (Abry & Veitch 1998, Zhao et al. 2019). Wavelet function self-oscillation may cause errors caused by pseudo-oscillation of signals. The error can be eliminated by analysing the wavelet coefficient of variation, and the amplitude and phase change information of the signal in the time series can be obtained simultaneously. The basic principle of Morlet wavelet analysis is as follows.

The form of wavelet generating function is:

$$\psi(x) = \pi^{1/4} e^{icx} e^{\frac{x^2}{2}} \quad \ldots(13)$$

Its subwavelet is:

$$\psi_{a,b}(x) = |a|^{-1/2} \psi\left(\frac{x-b}{a}\right) \quad \ldots(14)$$

Where, the parameter a represents the scale of expansion and the parameter b represents the translation distance. In the Fourier analysis, T has the following relationship with parameter a:

$$T = \frac{4\pi a}{c+\sqrt{2+c^2}} \quad \ldots(15)$$

The trend of time series and the information of time and position can be obtained by wavelet analysis. To obtain valuable information, the essence of the wavelet transform is to analyze one-dimensional signals in terms of time and frequency, to analyze the time-frequency structure of the climate system in detail. The wavelet coefficients obtained from the analysis are related to time and frequency, so the transformation results can be presented in a two-dimensional image.

When analysing the precipitation, the wavelet real part contour map can reflect the periodic changes of the precipitation series at different time scales and its distribution in the time domain, to judge the future trend of precipitation at different time scales. The contour curve is the real part value of the wavelet coefficient, and the real part value of the wavelet coefficient is positive, which represents abundant precipitation. Instead, it means less precipitation.

Precipitation mutation research method: Precipitation abrupt change refers to the sharp change of precipitation from one stable state to another stable state. The test and analysis of precipitation abrupt change is an important part of studying the long-term change characteristics of precipitation. When the statistical law of the data sample changes obviously at a certain moment, the moment point is called the change point. The discrimination of the variable point is generally considered from two different aspects: one is whether the numerical characteristics of the distribution change under the premise that the observed value distribution before and after the change point remains unchanged; The other is whether the distribution function of the observed value changes before and after the change point. The observed value originally obeys a certain distribution, but changes to another distribution after the change point. Mutation analysis by Mann-Kendall (M-K) method (Mann et al. 2015, Xiao et al. 2019): time series data $(x_1, x_2, \ldots x_n)$ is n independent samples with the same distribution of random variables, where m_i represents the cumulative count of the $i-th$ sample $x_i > x_j$ $(1 \leq j \leq i)$ and defines a statistic C_k:

$$c_k = \sum_{i=1}^{k} m_i \quad \ldots(16)$$

$$E(c_k) = k(k-1)/4 \quad \ldots(17)$$

$$\sigma(c_k) = k(k-1)(2k+5)/72 \quad \ldots(18)$$

$$UF_K = (c_k - E(c_k))/\sqrt{\sigma(c_k)} \quad \ldots(19)$$

Where $E(c_k)$, $\sigma(c_k)$ is the mean and variance of c_k, UF_K is the normalization of C_k. By reversed sequence data $(x_n, x_{n-1}, \cdots, x_1)$ repeat the above process, make $|UB_k| = -UB_k, k = n, n-1, \cdots, UB_1 = 0$. If the UF and UB curves intersect within the confidence interval, they are the possible abrupt transition points.

CASE ANALYSIS

Data Sources

Taking the annual precipitation data of the Yellow River Delta from 1954 to 2018 as an example, this paper studies and analyzes the evolution characteristics of annual precipitation in the Yellow River Delta. The location of the study area is shown in Fig. 1. The data were obtained from the China meteorological data website (http://data.cma.gov.cn/) and the Statistical Yearbook of Shandong province. The sequence independence test was conducted by Von Neuman's Q statistics. The test results showed that under the confidence level α = 0.05, the test statistics - Q was 1.724 and was not in the critical value. Therefore, the null hypothesis was accepted and the precipitation data from 1954 to 2014 were considered as independent samples.

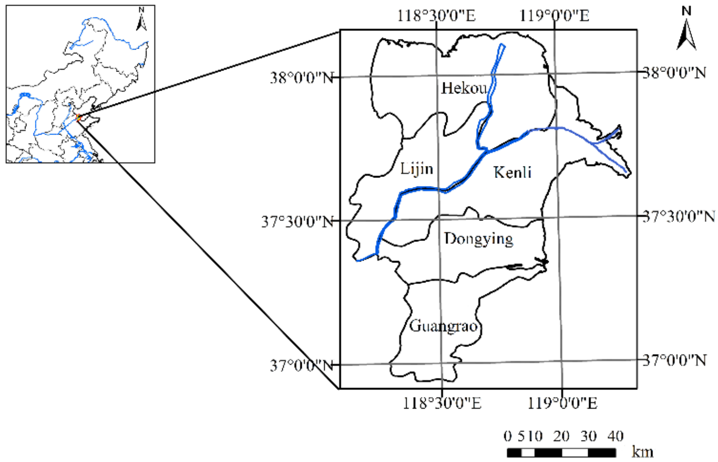

Fig. 1: The location map of the study area.

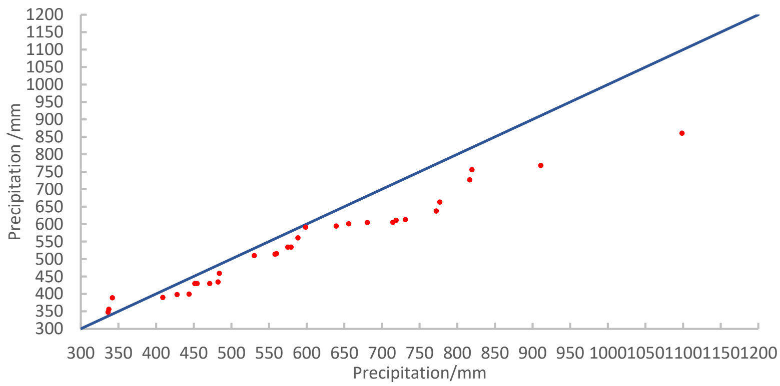

Fig. 2: Precipitation trend analysis.

Evolution Characteristic Analysis

Trend analysis: (1) ITA method was used to analyze the average annual precipitation for 61 consecutive years from 1954 to 2014, and the data of the first year was omitted. The first subsequence is 1955-1984, is the X-axis; The second subsequence is 1985-2014, which is the Y-axis. Draw the precipitation trend analysis diagram, and the analysis results are shown in Fig. 2.

ITA index D is calculated according to formula (2), as shown in Table 1.

As can be seen from Fig. 2, each point fell below the 1:1 line, showing a downward trend as a whole. When the precipitation is between 400mm-600mm, each point was close to the 1:1 line, with no obvious trend change. When the precipitation is between 650mm-800mm, the precipitation decreased significantly and gradually increased. However, at 800mm-850mm, the downward trend suddenly rebounded. When the precipitation reaches above 900mm, the downward trend became more obvious. At the same time, according to ITA index D in Table 1, the overall precipitation showed a downward trend, which gradually increased with the increase of precipitation.

Table 1: ITA index D.

Overall	Low	Medium	High
-9.48	-2.77	-5.87	-18.01

(2) R/S analysis was performed on the annual average precipitation for 61 consecutive years from 1954 to 2014, and the R/S annual precipitation diagram was drawn. The results are shown in Fig. 3.

Periodic analysis: (1) In order to clarify the implied period of the precipitation time series, different time series lengths were selected to determine the consistency and stability of the implied period of different time series lengths. Therefore the three-time series of 40, 50 and 60 years were selected. The maximum entropy power spectrum was shown in Fig. 4.

(2) The Morlet continuous complex wavelet transform

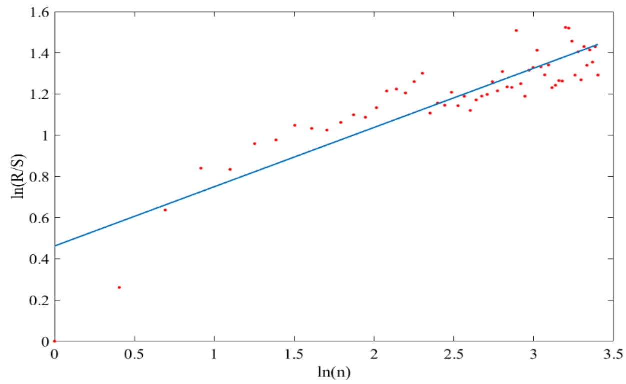

Fig. 3: R/S annual precipitation diagram.

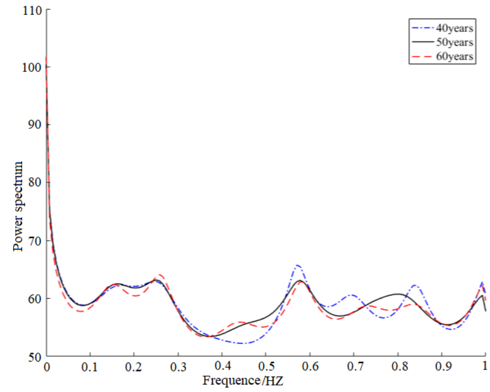

Fig. 4: MEM power spectrum of three precipitation sequences.

commonly used in the analysis of complex hydrological time series is selected to calculate the annual average precipitation of in the Yellow River, Shandong Province from 1954-2014. The wavelet coefficient transform diagram of precipitation and precipitation wavelet variance diagram are shown in Fig. 5 and Fig. 6 respectively.

Morlet continuous complex wavelet transform indicates that there were obvious interannual and chronological changes in precipitation, from top to bottom there were three-time scales of 20-32a, 8-18a, and 3-6a. The wavelet variance graph of precipitation suggests that there were three peaks of precipitation, corresponding to the time scale of 27, 13 and 5 years. Among them, the 27 year scale corresponds to the peak of wavelet variance and the period of oscillation are the strongest, which was the first main period of precipitation change, and plays a major role in the evolution of precipitation series. The second to third main periods of precipitation change were 13 and 5 years in turn. The three periods play a decisive role in the change characteristics of precipitation in the whole time domain of the Yellow River Delta, but the 27 year period is the main one

Precipitation mutation test: The M-k method is used to analyze the annual average precipitation of the meteorological station in the Yellow River Delta from 1954 to 2014. The calculation results are shown in Fig. 7.

According to the M-K mutation test, UF is a standard normal distribution with a significance level of 0.05. From 1954 to 1980, the curve of UF and UB showed an upward trend. In the 1960s, the curve of UF exceeded the critical line of confidence level. It intersected in 1980 and 2003. Since 1987, the curve of UF was less than 0. From 2002 to 2014, there were many intersections between the curve of UF and UB.

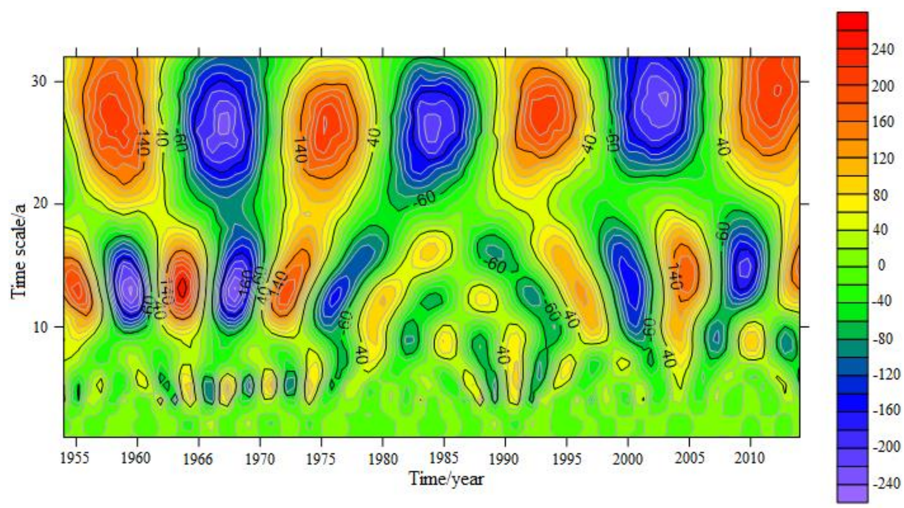

Fig. 5: Wavelet coefficient transform diagram of precipitation.

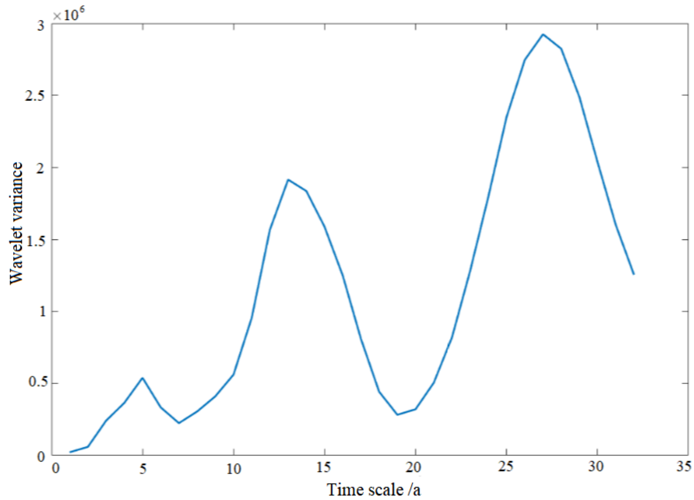

Fig. 6: Precipitation wavelet variance diagram.

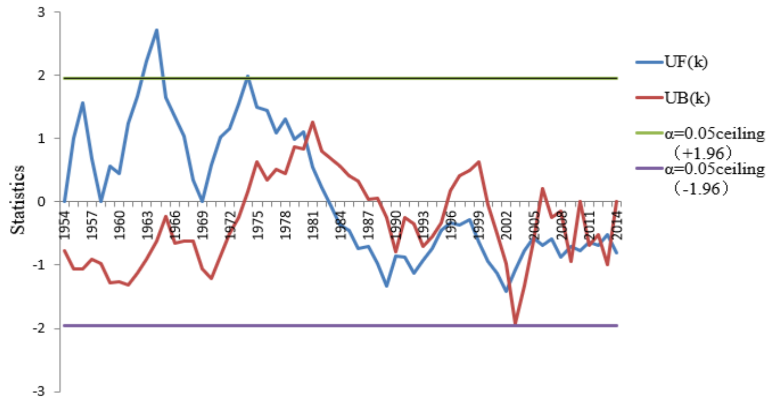

Fig. 7: M-K method mutation point test of annual average precipitation.

DISCUSSION

The precipitation trend analysis chart of 60 years is obtained by the ITA method. It indicates that the precipitation in the Yellow River Delta had a significant downward trend, and the downward trend increased gradually with the increase of precipitation. The results of R/S analysis suggest that the annual precipitation in this area showed a significant decreasing trend, which is consistent with the results of ITA analysis. In the future, the precipitation may show an increasing trend, and the trend is relatively strong.

The maximum entropy spectral analysis indicates that the optimal frequency value of the three sequence lengths was 0.24, the reciprocal was 4.167, and 5 years was chosen as the quasi period of the 61-year annual average precipitation sequence of the Yellow River Delta.

Morlet continuous complex wavelet transform indicates that there were three-time scales of precipitation: 20-32a, 8-18a, and 3-6a. From the scale of 20-32 years of analysis, the precipitation changes had a period of abundance - dry - abundance - dry - abundance - dry - abundance, with strong turbulence and globality. For this large-scale alternation of abundance and dry, the precipitation in Yellow River Delta showed a significant abrupt change characteristic. Specifically, before 1963, 1971-1980, 1988-1997, after 2007, the precipitation was abundant. 1963 -1970, 1981-1987, 1998-2007, the precipitation was poor. By 2014, the contours have not been closed, indicating that the period after 2014 is in an abundant period. At this time, the periodic variation of precipitation was localized on the large time scale and the vibration was the strongest. From the 8-18 year scale analysis, the precipitation had 13 periods of abundance and dry alternating. Specifically, before 1957, 1963-1965, 1971-1974, 1978-1985, 1995-1998, 2003-2006, after 2012, the precipitation was abundant. 1958-1962, 1966-1970, 1975-1977, 1986-1994, 1999-2002, 2007-2011, the precipitation was poor. For the change of precipitation on a smaller scale below 8 years, the shock centre in 1954-1990 is 4a. At this time, the change of the runoff period was the weakest on the small time scale. The results of Morlet continuous complex wavelet transform and R-S analysis are consistent with each other.

According to the M-K mutation test, UF is a standard normal distribution with a significance level of 0.05. Observing the UF and UB curves, the precipitation was larger during 1954-1980, showing an upward trend. During the 1960s, the UF curve exceeded the confidence level critical line and precipitation increased significantly. UF and UB curves intersected in 1980 and 2003. Influenced by the sudden change of sunspot and earth rotation period, the precipitation changed abruptly in 1980 and 2003. Since 1987, the UF curve has been less than 0, indicating a downward trend in precipitation. UF and UB curves have multiple intersections. Combined with trend analysis results, there was no significant mutation time in the annual precipitation in this region from 2002 to 2014. The reason may be that the annual natural precipitation is small. The annual natural precipitation change is more sensitive to the impact of heavy rainfall, and the relative variation of precipitation is large, resulting in poor precipitation variation and complex mutations. In addition, the impact of human activities is also an important reason for the complexity of precipitation mutations.

CONCLUSIONS

1. The analysis of ITA indicates that the precipitation in the Yellow River Delta had a significant downward trend in the past 61 years, and the downward trend gradually increased with the increase of precipitation. The R/S analysis suggests that the annual precipitation in the region had a significant downward trend in the past 61 years, which is consistent with the results of ITA analysis. However, the precipitation may show an upward trend in the future, and the trend is relatively strong.
2. The quasi-period of 61 annual precipitation in the Yellow River delta was about 5 years, which is consistent with the small scale oscillation period obtained by wavelet analysis based on maximum entropy spectral analysis and Burg recurrence theory.
3. According to the M-K mutation test, during 1954-1980, the precipitation showed an upward trend. In the 1960s, the trend is obvious. In contrast, it showed a downward trend after 1987. In 1980 and 2003, the precipitation had a mutation. In 2002-2014, there was no significant mutation time point.
4. Although this paper comprehensively evaluates the evolution characteristics of precipitation, it doesn't consider the physical mechanism of precipitation change. There are some shortcomings, which need to be further optimized.

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