Diagnosis of the Evolutionary Characteristics and Variability of Meteorological Drought in the Yellow River Basin

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Abstract: Frequent occurrences of meteorological droughts in the Yellow River Basin (YRB) result from the combined impact of global climate change and human activities. To address the problems of unclear evolution mechanism and difficulty in accurately determining the variability time of meteorological droughts in the basin, this study uses multi-scale Standardized Precipitation Evapotranspiration Index (SPEI) and integrates wavelet analysis with the Mann-Kendall to investigate the evolution patterns and variability characteristics of meteorological droughts in the basin. The findings indicate that: (1) Meteorological drought shows a trend of shifting from the upper to the middle and lower reaches of the river, with clear seasonal and interannual variability trends. (2) The basin experiences six primary drought periods, with durations ranging from 2 to 6 months and 10 to 18 months, the latter being particularly noteworthy. (3) The main periods of meteorological drought variability are concentrated from 03/2001 to 10/2014, from 06/2006 to 08/2006, from 10/2017 to 01/2019, and 11/2019. This study furnishes a scientific groundwork for enhancing water resource management in the YRB and elucidating the mechanisms underlying meteorological drought evolution. These insights contribute to fostering ecological preservation and facilitating high-quality development within the basin.

1. Introduction

Droughts are frequent, prolonged and widespread [1]. Statistical data indicates that since 1990, global drought disasters have resulted in an average of USD 8 billion in direct economic losses. This underscores a significant challenge to global food security, economic stability, and environmental integrity [2]. In the past few years, notable temperature rises within river basins have resulted in a marked uptick in drought occurrence and intensity, presenting substantial threats to the ecological balance and water stability of these regions. Hence, understanding the mechanisms of drought evolution and accurately identifying the timing of drought variations in river basins has become a focal point of research among scholars both domestically and internationally, with the following results:

Drought, as a complex systemic problem, can be influenced by imbalances in any part of the natural water cycle, affecting its occurrence and development. The mechanisms behind drought are difficult to describe completely and accurately [3-4]. For instance, Huang et al. [5] employed the SPEI and SRI to delineate meteorological and hydrological droughts in the Wei River basin, revealing discernible seasonal trends in their progression. Wen et al. [6] investigated research on the driving mechanisms of drought using meteorological data and the SPEI index, which indicated that precipitation and temperature play a dominant role in driving drought. In addition, researchers have also investigated drought level thresholds and abrupt changes based on sensitivity analysis and overall classification accuracy. For example, Zhang et al. [7] applied information diffusion to establish standards for drought index risk levels, providing quantitative assessments of drought severity. Chen et al. [8] used the sliding t-test and sliding F-test methods, based on the PDSI index to identify the years of climatic abrupt changes in the Dingxi area of Gansu between 1958 and 2010.

In summary, current research on drought in the Yellow River basin still faces limitations such as a singular focus on indices, vague mechanisms of evolution, difficulties in grasping the alternation of dry and wet conditions, and imprecise identification of abrupt changes. Therefore, this paper, based on different time scales and using wavelet analysis and the MK trend test method, this paper conducts analyses of drought evolution characteristics and tests for abrupt changes. The initiatives are directed towards ameliorating the deficiencies observed in current research, bearing substantial importance in guaranteeing water security and promoting high-quality development.

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2. Research background

2.1. Research area

The Yellow River stands as one of China's and the world's most significant rivers, commanding attention due to its rich historical, cultural, and geographical significance [9]. The basin of the Yellow River holds the narrative of ancient Chinese civilization. Revered as the cradle of Chinese heritage, it nurtured pivotal civilizations like the Xia, Shang, and Zhou dynasties. Over its extensive timeline, the basin bore witness to the flourishing of agrarian culture, hydraulic ingenuity, and cultural exchange, imprinting an indelible mark on the socio-economic fabric of ancient China. Yet, with the tide of industrialization and urbanization, the ecological equilibrium of the Yellow River Basin wanes, marred by issues such as rampant water resource exploitation, soil degradation, recurrent flooding, and debilitating droughts. These environmental tribulations not only imperil the livelihoods of local denizens but also cast a pall over China's ecological equilibrium and resonate globally. Hence, delving into the intricacies of meteorological drought evolution within the Yellow River Basin assumes paramount importance. Such an endeavor deepens comprehension of climate change's ramifications on drought, furnishing a scientific underpinning for regional water resource governance and drought crisis mitigation [10]. This pursuit, thus, emerges as a pivotal cornerstone in safeguarding the ecological sanctity and socio-economic prosperity of the Yellow River Basin. Research area is shown in Figure 1.

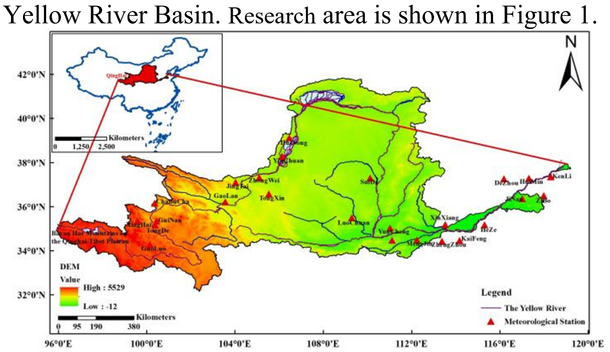

Fig. 1. Research area

2.2. Data

This study concentrates on the Yellow River Basin, examining the evolutionary characteristics and variability of meteorological drought within the basin. Utilizing the monthly-scale Standardized Precipitation Evaporation Index (SPEI), data from 25 meteorological stations (including Xinhai, Gaolan, Guinan, Zhongwei, Suide, Yuncheng, Zhengzhou, Kaifeng, Zibo, Kenli, among others) spanning from January 2001 to December 2020. Rigorous screening and integrity checks were conducted to enhance data quality, providing a robust foundation for the investigation into meteorological drought within the basin.

3. Methodology

3.1. Standardized precipitation evapotranspirati on index (SPEI)

The SPEI is capable of representing the dry–wet conditions and deviations of a region over a long time series, and serves as a crucial index for analysing the historical evolution of meteorological drought trends [11]. By considering the differences between precipitation and potential evapotranspiration, the cumulative effects of meteorological drought in different regions and at different timescales are revealed. SPEI can comprehensively reflect drought conditions from different perspectives and shows great promise for applications [12]. Moreover, the Standardized Precipitation Evapotranspiration Index (SPEI) enables the evaluation of drought intensity across temporal and geographical dimensions, offering perspectives on temperature fluctuations and extreme temperature effects beyond the scope of global climate change. The cumulative density function was standardized.

(1) PET was calculated using the Thornthwaite method [13] with the following formula:

$$PET = \begin{cases} 0 & T < 0 \\ 16(\frac{N}{12})(\frac{NDM}{30})(\frac{10T}{I})^m & 0 \le T < 26.5 \\ -415.85 + 32.24T - 0.43T^2 & T \ge 26.5 \end{cases} \quad (1)$$

Here, T represents the mean monthly temperature, N denotes the maximum hours of sunshine, and NDM signifies the number of days per month. I stands for the annual calorific index, calculated as follows:

$$I = \sum_{i=1}^{12} \left(\frac{T}{5}\right)^{1.514} \qquad T > 0 \quad (2)$$

m is a coefficient related to I and is calculated as follows:

$$m = 6.75\times10^{-7} I^3 - 7.71\times10^{-5} I^2 + 1.79\times10^{-2} I + 0.492 \quad (3)$$

(2) The cumulative value Di was computed as the disparity between precipitation and potential evapotranspiration (PET).

$$D_i = P_i - PET_i \quad (4)$$

$$D_{i,j}^k = \begin{cases} \sum_{m=13-k+j}^{12} D_{i-1,m} + \sum_{m=1}^{j} D_{i,m} & j < k \\ \sum_{m=j-k+1}^{j} D_{i,m} & j \ge k \end{cases} \quad (5)$$

where $D_{i,j}^k$ is the cumulative precipitation evapotranspiration difference over k months starting in month j of year i.

(3) Fitting the numerical sequence D_i using a log-logistic distribution,

$$\begin{cases} \beta = \frac{2\omega_1 - \omega_0}{6\omega_1 - \omega_0 - 6\omega_2} \\ \alpha = \frac{(\omega_0 - 2\omega_1)\beta}{\Gamma(1+1/\beta)\Gamma(1-1/\beta)} \\ \gamma = \omega_0 - \alpha\Gamma(1+1/\beta)\Gamma(1-1/\beta) \end{cases} \quad (6)$$

The cumulative probability distribution function for D_i is as follows:

$$F(x)=\left[1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1} \qquad P=1-F(x) \tag{7}$$

where α,β,γ are parameters obtained by fitting using the method of moments, $\Gamma(\beta)$ is a Gamma function of β, and P is the cumulative probability. When $P \leq 0.5$, the probability weight of D_i is $\omega=\sqrt{-2\ln P}$. When $P>0.5$, P is replaced by $1-P$, and S takes the opposite value.

(4) The sequence was transformed into a standardized normal distribution.

$$SPEI=\begin{cases}\omega-\dfrac{c_0+c_1\omega+c_2\omega^2}{1+d_1\omega+d_2\omega^2+d_3\omega^3} & P\leq 0.5\\ -(\omega-\dfrac{c_0+c_1\omega+c_2\omega^2}{1+d_1\omega+d_2\omega^2+d_3\omega^3}) & P>0.5\end{cases} \tag{8}$$

where c_0=2.515517, c_1=0.802853, c_2=0.010328, d_1=1.432788, d_2=0.189269, and d_3=0.001308.

The drought classifications are shown in Table 1, from mild to severe as mild, moderate, moderate and Extreme drought.

Table 1. Drought classification table

Type	Indexes	Drought classification				
		Normal	Mild	Moderate	Severe	Extreme
Meteorological drought	SPEI	(-0.5, ∞)	(-1.0, -0.5]	(-1.5, -1.0]	(-2, -1.5]	(−∞ , -2]

3.2. Continuous wavelet transform（CWT）

Wavelet analysis is a common method and theory for the periodic characterisation of hydrometeorological time series data. The method not only demonstrates the local characteristics of the data, but also captures the transient characteristics of the data very sensitively [14].

(1) Morlet analysis is a time-frequency domain analytical method which is defined for any $f(t)\in L^2(R)$:

$$w_f(a,b)=|a|^{0.5}\int_{-\infty}^{+\infty} f(t)\overline{\psi}(\frac{t-b}{a})dt \tag{9}$$

where $w_f(a,b)$ is the wavelet transform coefficients, a is the scale factor, b is the translation factor, $\overline{\psi}(t)$ is the basis wavelet, $f(t)$ is the original signal.

(2) The Morlet wavelet is utilized to perform continuous wavelet transformation on time series data, described by the subsequent formula:

$$\psi(t)=\pi^{-1/4}e^{i\omega_0 t-t^2/2} \tag{10}$$

Where ω_0 is the nondimensional frequency, t is the nondimensional time. Morlet wavelet ($\omega_0=6$) is a good choice when dealing with features because it weighs time and frequency.

(3) The equation for the wavelet energy spectrum is expressed as:

$$W_{XY}(\alpha,\tau)=C_X(\alpha,\tau)C_X^*(\alpha,\tau)=|C_X(\alpha,\tau)|^2 \tag{11}$$

Where $C_X(\alpha,\tau)$ denotes the wavelet transform coefficient of $x(t)$,and * stands a complex conjugate.

(4) For the continuous wavelet transform energy spectrum, red noise is generally used as the background spectrum for testing, and the testing process is modelled by the first-order autoregressive equation (AR1), with the background red noise power defined as:

$$p_k=(1-r)/(\left|1-re^{-2i\pi k}\right|) \tag{12}$$

The correlation coefficient *(r)* of the autoregressive equation within the red noise power spectrum is calculated with respect to the Fourier frequency index *(k)*. Typically, the values for each scale within the wavelet cone of influence are determined at the 95% confidence level.

3.3. Mann-Kendall variant diagnosis (MK)

Mann-Kendall is a climate diagnostic and predicting technique based on non-parametric hypothesis testing that determines the presence or absence of mutations in meteorological drought sequences and identifies when they occur. The principle is to detect monotonic trends (upward, downward, or no trend) in time series data by comparing the magnitude of each data point with its predecessor [15]. The Mann-Kendall test assumes the null hypothesis that the series is independently and identically distributed, with the alternative hypothesis suggesting the presence of a monotonic trend. If the P-value falls below a predefined significance level (typically 0.05), the null hypothesis is rejected, indicating the presence of a monotonic trend [16]. The calculation process is as follows:

$$S_k=\sum_{i=1}^{k} r_i, r_i=\begin{cases}1 & X_i>X_j\\ 0 & X_i\leq X_j\end{cases} \quad (j=1,2,\ldots,i \quad k=1,2,\ldots,n) \tag{13}$$

where $\{X_n\}$ is the SPEI 1 sequence, S_k is the cumulative number of $X_i>X_j (1\leq j\leq i)$.

The mean and variance of the statistic S_k are as follows:

$$\begin{cases}E[S_k]=k(k-1)/4\\ Var[S_k]=k(k-1)(2k+5)/72 \quad 1\leq k\leq n\end{cases} \tag{14}$$

Standardized new sequence S_k:

$$UF_k=\frac{(S_k-E[S_k])}{\sqrt{Var[S_k]}} \tag{15}$$

Where $UF_1=0$. α is used as the significant level for matching the sequence, and if $|UF_k|>U_\alpha$, it indicates a significant change in the trend of the sequence. Calculate the anti-sequence $\{x_n\}$ of this sequence by applying the same method to this sequence, i.e., $\{x_n\}=\{X_n,\cdots,X_2,X_1\}$. A similar operation is then performed with a new sequence UF_k, and the

UB_k of the anti-sequence is given by the following equation:

$$\begin{cases} UB_k = -UF_{k'} \\ k = n+1-k' \end{cases} \qquad k = 1, 2, \ldots, n \qquad (16)$$

4. Results

4.1. Characteristics of the spatial and temporal evolution of meteorological drought

The Standardized Precipitation Evapotranspiration Index (SPEI) stands as a globally recognized drought index.

This study examines the evolutionary trends of meteorological drought in the YRB over the past twenty years. The analysis utilizes SPEI indices (series 1, 3, and 12) at various temporal scales with a spatial resolution of 1-km, covering the period from 2001 to 2020 in China. Findings are presented in Figure 2 and Table 2, delineating the monthly, seasonal, and annual drought evolution characteristics of the basin in Figures 2(a)-2(c), respectively.

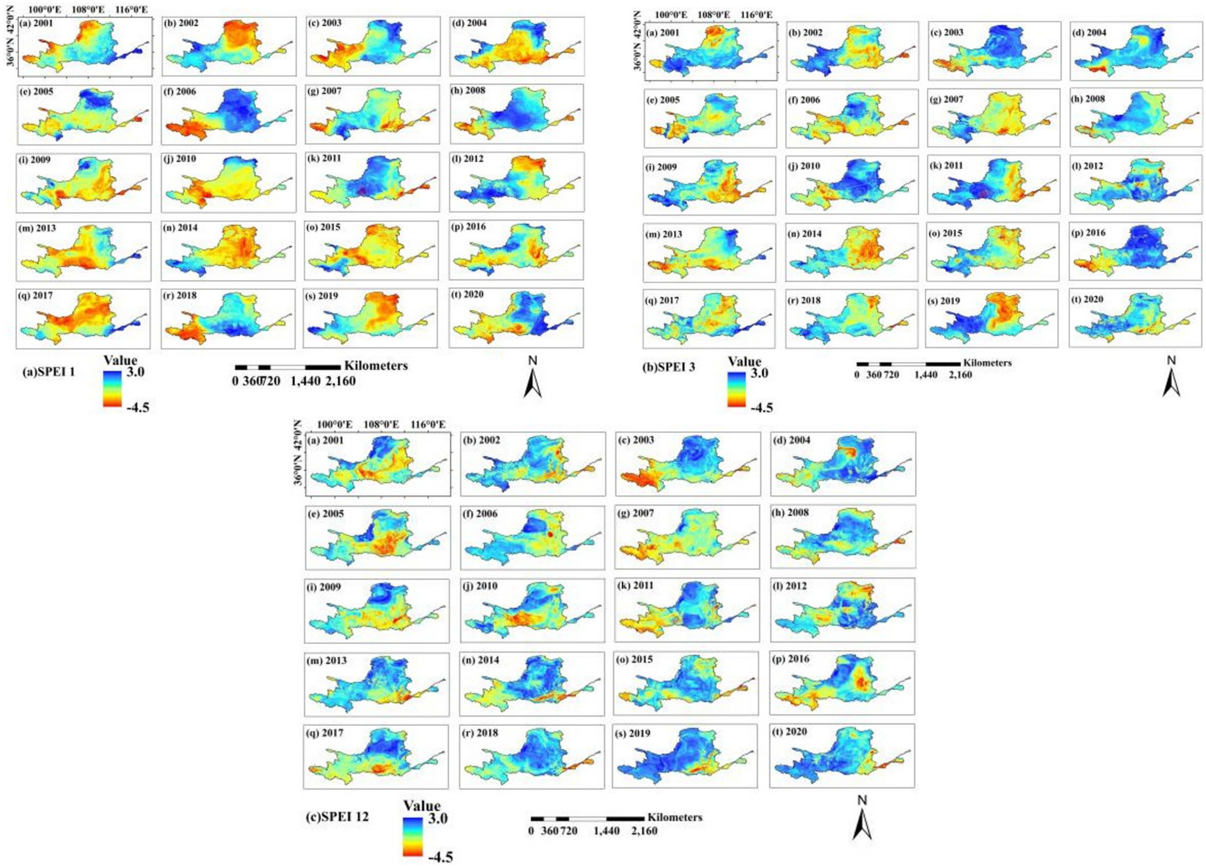

Fig. 2. Spatial and temporal evolution characteristics of drought

Table 2. Multi-scale SPEI values

Year	Index scales						Year	Index scales					
	SPEI 1		SPEI 3		SPEI 12			SPEI 1		SPEI 3		SPEI 12	
	Max	Min	Max	Min	Max	Min		Max	Min	Max	Min	Max	Min
2001	2.22	-2.03	1.68	-1.17	1.87	-2.42	2011	1.62	-1.74	1.20	-4.44	1.56	-2.01
2002	1.72	-2.87	1.52	-1.47	1.28	-2.95	2012	1.89	-2.12	2.28	-1.30	1-95	-2.26
2003	1.74	-1.19	1.49	-1.64	1.92	-3.64	2013	1.72	-1.64	1.92	-3.39	2.09	-2.70
2004	1.61	-1.07	1.76	-2.03	2.08	-1.63	2014	-0.04	-3.06	1.37	-3.13	1.80	-2.81
2005	1.26	-1.34	1.77	-1.52	2.02	-1.87	2015	1.58	-1.65	1.35	-2.95	1.96	-2.31
2006	2.15	-2.60	1.90	-2.12	2.17	-2.24	2016	1.09	-1.36	2.01	-2.14	1.79	-2.61
2007	0.90	-1.67	1.57	-1.48	1.87	-2.38	2017	1.42	-1.99	1.34	-2.54	2.09	-2.21
2008	2.34	-0.58	1.91	-1.52	2.02	-1.49	2018	2.15	-1.96	1.61	-3.27	1.77	-1.79
2009	0.72	-2.76	0.99	-3.78	1.60	-2.67	2019	1.76	-2.32	1.99	-3.22	1.99	-2.64
2010	1.58	-2.37	1.75	-2.56	1.49	-2.30	2020	2.15	-0.70	1.97	-0.86	1.70	-2.46

As shown in Figure 2 and Table 2, the Yellow River Basin in the monthly scale (Figure 2(a)) shows the climatic characteristics of aridity in the upper reaches, semi-drought in the middle reaches, and humidity in the lower reaches. Combined with Figure 2(a), the trend of drought in the basin is clearly shifted, and the study period shows the trend from upstream to middle and downstream, especially in 2004, 2009, 2010, 2013-2015, and 2017, more than 80% of the basin is in drought, which is a significant feature. In addition, as shown in Table 2, the minimum SPEI value of the watershed at the monthly scale was -3.06, which appeared in 2014, reaching the extreme drought class.

From Figure 2(b) and Table 2, it is known that the basin showed a relatively balanced dry and wet state at the seasonal scale, with the drought characteristics of the basin being more significant in 2006, 2007, 2014 and 2019. In addition, the minimum SPEI value of the basin was -4.44, which appeared in 2011 and reached the extreme drought level, and the mean SPEI value of the basin was -2.33 during the study period, which made the inter-seasonal drought very serious.

From Figure 2(c) and Table 2, it is known that the basin as a whole has mild drought climate characteristics at the annual scale, but in individual years, the basin is characterized by drought, and the extreme drought climate is significant. Among them, extreme drought occurred in the upper part of the basin with an SPEI value of -3.64 in 2003, severe meteorological drought in the middle part of the basin in 2005, and severe meteorological drought in the lower part of the basin in 2018. In addition, the mean SPEI value of the basin is -2.37, which is consistent with the monthly and seasonal scales, and the extreme climate events in the basin are significant.

In summary, meteorological droughts in the basin showed a trend of shifting from upstream to midstream and downstream during the study period, with downstream meteorological droughts becoming more and more significant and deepening year by year as time goes by. The smaller the scale, the more accurate the SPEI is in identifying droughts in the basin, and it is able to identify the beginning and end of meteorological droughts in time. In addition, in recent years, the basin has experienced significant alternation of wet and dry conditions, which makes it highly susceptible to inter-seasonal and inter-annual droughts, as well as drought-flood abrupt alternation events, and the relevant authorities should take appropriate measures to prevent the serious threats posed by drought-flood abrupt alternation events.

4.2. Meteorological drought period characteristics

The application of continuous wavelet transform effectively captures the localized features inherent in meteorological drought series while also discerning transient characteristics. This enables a deeper exploration of latent information and patterns embedded within time series data, thereby elucidating the temporal and spatial trends and cyclic characteristics of meteorological drought within the watershed. Figure 3 illustrates the continuous wavelet power spectrum of the Yellow River basin.

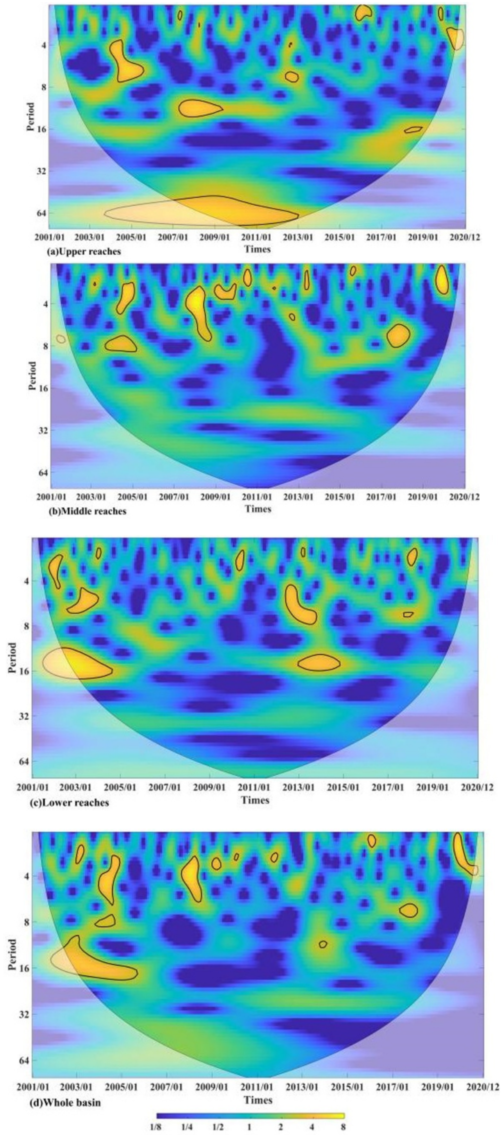

Fig. 3. The continuous wavelet power spectrum of the Yellow River Basin

Analysis of Figure 3(a) shows that there are six drought cycles in the upper Yellow River basin during the study period, which are 1-2 months, 3-5 months, 4-8 months, 6-7 months, 10-12 months and 56-72 months, and the drought cycle is as long as 16 months in 2007-2013. Analyzing Figure 3(b), it is known that there are four main cycles in the midstream, which are 7-9 months, 2-8 months, 6-10 months and 1-3 months, and the longest drought cycle is 8 months, which occurred in 2008-2009. Analyzing Figure 3(c), we know that there are four main cycles in the downstream, which are 10-18 months, 5-6 months, 6-8 months and 14-16 months, and the longest drought cycle is 6 months, which occurred in 2002-2005. In summary, together with Figure 3(d), we know that there are main cycles of 10-18 months, 2-6 months and 1-4 months in the whole basin, and the drought cycles are mainly distributed in 2002-2006 and 2013-2015, which indicates that seasonal and inter-annual meteorological droughts occur more frequently in the basin, and the droughts last longer.

4.3. Diagnosis of meteorological drought variability

In this section, we utilized the SPEI for January 2001/01-2020/12 to conduct MK mutation analysis on the meteorological drought variability over the study period. The results, depicted in Figure 4, are evaluated with a significance level of $\alpha = 0.05$, corresponding to critical values of ± 1.96. By plotting the UFk and UB_k curves alongside the ± 1.96 threshold lines, trends can be discerned. A positive (negative) value of UF_k indicates an upward (downward) trend, and surpassing the critical line signifies statistical significance. The time span exceeding the critical line denotes the period of mutation occurrence. In cases where the UF_k and UB_k curves intersect within the critical line, the moment of intersection marks the onset of mutation.

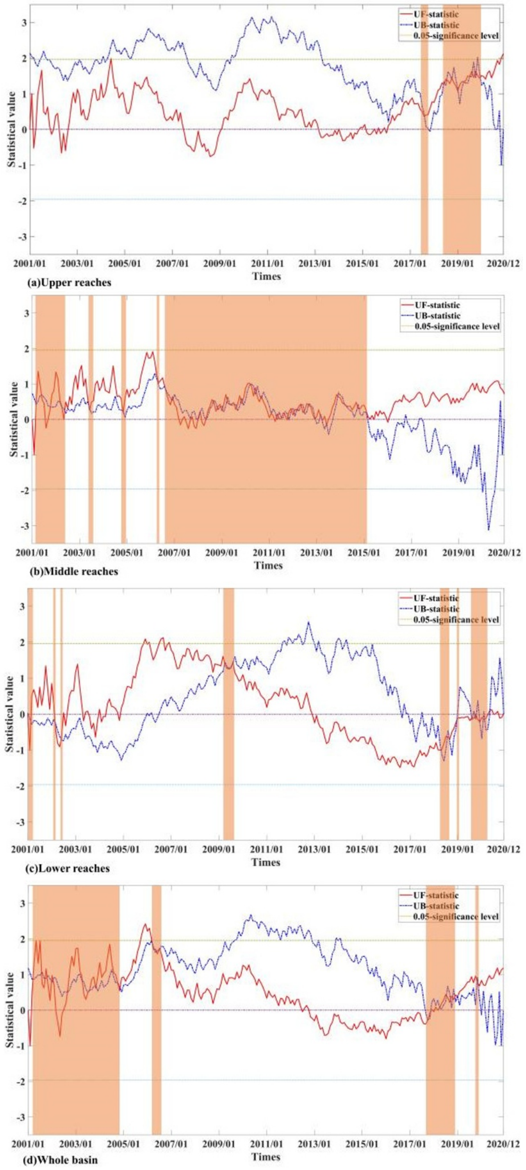

Fig. 4. The trends in variance testing in the Yellow River Basin

From the analysis of Figure 4(a), it is known that the meteorological drought sequence in the upper reaches of the Yellow River Basin changes abruptly in 06/2017 and 10/2018-01/2020, respectively. From Figure 4(b), it is known that the sudden change of meteorological drought sequence in the middle reaches is from 03/2001-10/2002, 06/2003, 10/2004, 01/2006 and 10/2006-09/2014, respectively. From Figure 4(c), the downstream 01/2001-03/2001, 02/2002, 08/2002, 03/2009, 06/2018-08/2018, 01/2019, and 10/2019-03/2020. In summary, combined with Figure 4(d), it is known that the meteorological drought sequences of the Yellow River Basin are concentrated in the time of abrupt changes in 03/2001-10/2014, 06/2006-08/2006, 10/2017-01/2019 and 11/2019, respectively. This indicates that meteorological drought mutations are frequent in the Yellow River Basin, and drought-flood abrupt alternation events such as drought-to-flood and flood-to-drought are frequent. Especially in the middle reaches, sudden meteorological drought events occur frequently, with high variability significance and long duration, bringing serious threats to the water security of the basin.

5. Discussion

Research on the characteristics and variability of meteorological drought in the Yellow River Basin unveils a diverse array of features exhibited by drought events across different time scales, likely influenced by atmospheric circulation and anomalies in sea surface temperature [17]. Meteorological drought is intimately linked with climatic elements such as surface temperature and precipitation variability, significantly impacting the local ecological environment and socio-economic landscape. Diagnosis of drought variability necessitates comprehensive analysis spanning interannual, seasonal, and long-term trends. Employing statistical methods and spatiotemporal analysis techniques allows for a deeper exploration of the spatiotemporal distribution patterns of drought events, facilitating an examination of the interrelationships and underlying mechanisms across various time scales [18]. To address the implications of this research, bolstered monitoring and observation systems are imperative, enhancing early warning systems and response capabilities for drought events. Further investigation into the mechanisms through which climate change influences drought, coupled with strengthened analysis and prediction of drought causation, will provide crucial support for drought disaster prevention and mitigation. Promoting interdisciplinary collaboration and considering various factors such as meteorology, hydrology, and ecology will drive sustainable development in both the ecological and socio-economic aspects of the Yellow River Basin.

Although certain results were obtained in this study, there are still some limitations. On the one hand, there are many types of droughts that need to be studied comprehensively by researchers, and scholars need to study droughts in watersheds from multiple levels and perspectives. On the other hand, the applicability of the methods and computational models in this study in areas with no information or a lack of data needs to be further investigated. In future research, we can consider multimodal data, such as videos, remote sensing, and images, to further explore the response relationship between different types of droughts and perform a comprehensive evaluation of droughts at multiple levels and from multiple perspectives.

6. Conclusion

Based on multi-scale SPEI, this paper investigates the evolution characteristics and variability of meteorological droughts in the basin. The following conclusions were obtained:

(1) There is a clear trend of seasonal and interannual drought changes, with a high risk, and the smaller the scale of the SPEI index. Meteorological droughts show a trend of shifting from upstream to downstream.

(2) There are 6 main cycles within the entire basin, among which the 2-6 month and 10-18 months cycles are more significant.

(3) The abrupt changes in the meteorological drought sequence are mainly concentrated in 03/2001-10/2014, 06/2006-08/2006, 10/2017-01/2019, and 11/2019.

In summary, this paper exhibits a pattern of development shifting from upstream to downstream, with increasingly frequent alternation between dry and wet periods. This study provides theoretical support for the implementation of for drought disaster prevention strategies within the basin.

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