

Phasic and periodic change of drought under greenhouse effect

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Abstract

Purpose – Drought is the primary disaster that negatively impacts agricultural and animal husbandry production. It can lead to crop reduction and even pose a threat to human survival in environmentally sensitive areas of China (ESAC). However, the phases and periodicity of drought changes in the ESAC remain largely unknown. Thus, this paper aims to identify the periodic characteristics of meteorological drought changes.

Design/methodology/approach – The potential evapotranspiration was calculated using the Penman–Monteith formula recommended by the Food and Agriculture Organization of the United Nations, whereas the standardized precipitation evaporation index (SPEI) of drought was simulated by coupling precipitation data. Subsequently, the Bernaola-Galvan segmentation algorithm was proposed to divide the periods of drought change and the newly developed extreme-point symmetric mode decomposition to analyze the periodic drought patterns.

Findings – The findings reveal a significant increase in SPEI in the ESAC, with the rate of decline in drought events higher in the ESAC than in China, indicating a more pronounced wetting trend in the study area. Spatially, the northeast region showed an evident drying trend, whereas the southwest region showed a wetting trend. Two abrupt changes in the drought pattern were observed during the study period, namely, in 1965 and 1983. The spatial instability of moderate or severe drought frequency and intensity on a seasonal scale was more consistent during 1966–1983 and 1984–2018, compared to 1961–1965. Drought variation was predominantly influenced by interannual oscillations, with the periods of the components of intrinsic mode functions 1 (IMF1) and 2 (IMF2) being 3.1 and 7.3 years, respectively. Their cumulative variance contribution rate reached 70.22%.

Research limitations/implications – The trend decomposition and periods of droughts in the study area were analyzed, which may provide an important scientific reference for water resource management and agricultural production activities in the ESAC. However, several problems remain unaddressed. First, the SPEI considers only precipitation and evapotranspiration, making it extremely sensitive to temperature increases. It also ignores the nonstationary nature of the hydrometeorological water process; therefore, it is prone to bias in



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drought detection and may overestimate the intensity and duration of droughts. Therefore, further studies on the application and comparison of various drought indices should be conducted to develop a more effective meteorological drought index. Second, the local water budget is mainly affected by surface evapotranspiration and precipitation. Evapotranspiration is calculated by various methods that provide different results. Therefore, future studies need to explore both the advantages and disadvantages of various evapotranspiration calculation methods (e.g. Hargreaves, Thornthwaite and Penman–Monteith) and their application scenarios. Third, this study focused on the temporal and spatial evolution and periodic characteristics of droughts, without considering the driving mechanisms behind them and their impact on the ecosystem. In future, it will be necessary to focus on a sensitivity analysis of drought indices with regard to climate change. Finally, although this study calculated the SPEI using meteorological data provided by China's high-density observatory network, deviations and uncertainties were inevitable in the point-to-grid spatialization process. This shortcoming may be avoided by using satellite remote sensing data with high spatiotemporal resolution in the future, which can allow pixel-scale monitoring and simulation of meteorological drought evolution.

Practical implications – Under the background of continuous global warming, the climate in arid and semiarid areas of China has shown a trend of warming and wetting. It means that the plant environment in this region is getting better. In the future, the project of afforestation and returning farmland to forest and grassland in this region can increase the planting proportion of water-loving tree species to obtain better ecological benefits. Meanwhile, this study found that in the relatively water-scarce regions of China, drought duration was dominated by interannual oscillations (3.1a and 7.3a). This suggests that governments and nongovernmental organizations in the region should pay attention to the short drought period in the ESAC when they carry out ecological restoration and protection projects such as the construction of forest reserves and high-quality farmland.

Originality/value – The findings enhance the understanding of the phasic and periodic characteristics of drought changes in the ESAC. Future studies on the stress effects of drought on crop yield may consider these effects to better reflect the agricultural response to meteorological drought and thus effectively improve the tolerance of agricultural activities to drought events.

Keywords Standardized precipitation evapotranspiration index, Meteorological drought, Spatiotemporal change, Periodicity

Paper type Research paper

1. Introduction

The threat posed by both dry and wet climate change to regional water resources, ecological security and sustainable social and economic development is increasingly prominent (Liu *et al.*, 2023; Chen *et al.*, 2015a; Restrepo-Coupe *et al.*, 2023; Xu *et al.*, 2023). Drought, a natural disaster causing crop reduction, water shortages for both humans and animals, vegetation dieback, desertification and forest fires (Park *et al.*, 2016; Yu *et al.*, 2019), has attracted significant attention from the scientific community and society (Zhang and Shen, 2019). Furthermore, with its long duration, large scope, wide impact range and substantial follow-up impact (Zhao *et al.*, 2021), droughts cause social and economic losses far surpassing those of other disasters (Zhang *et al.*, 2017). The Sixth Assessment Report of the Intergovernmental Panel on Climate Change clearly states that climate change exacerbates the water cycle, affecting rainfall patterns and resulting in extreme rainfall events and severe droughts. In China, the frequency, duration and extent of droughts have significantly increased (Yu *et al.*, 2014; Chen and Sun, 2015; Zhang *et al.*, 2017; Liao and Zhang, 2017), especially in northern regions (Wang *et al.*, 2014). Arid and semiarid regions are experiencing significant expansion amid climate change (Huang *et al.*, 2016, 2017; Zheng *et al.*, 2013). With global warming, arid regions are becoming drier, whereas humid regions are becoming wetter (Zhao *et al.*, 2014). Climate change strongly disrupts the dry and wet conditions of environmentally sensitive areas of China (ESAC) leading to changes in regional water resource distribution and triggering a series of changes in resources, ecological environments and society. Therefore, accurately depicting and analyzing

meteorological drought patterns, phases and evolutionary processes in environmentally sensitive areas is crucial for addressing the challenges posed by global climate change.

Several drought indices are used to represent meteorological drought events (Zargar *et al.*, 2011; Zhong *et al.*, 2023) but there is inconsistency in the required variables and calculation methods. Moreover, the complexity and regional climate variations, along with geographical diversity, significantly impact the scientific relevance of drought index applicability (Mishra and Singh, 2009). Mainstream drought indicators include the palmer drought severity index (PDSI), standardized precipitation index (SPI) and standardized precipitation evapotranspiration index (SPEI). The SPI, proposed by McKee *et al.* (1993), incorporates precipitation data and adequately reflects drought conditions across different timescales and regions. However, its limitation lies in its failure to consider other background factors, restricting its applicability. Conversely, the PDSI considers the impact of temperature and early weather conditions on drought but entails a complex calculation process and difficult access to required parameters. In addition, its fixed time scale makes it difficult to represent multi-timescale droughts (Vicente-Serrano *et al.*, 2011). Vicente-Serrano *et al.* (2010) constructed an SPEI by introducing multiple climatic factors based on the SPI and integrating the advantages of both the PDSI and SPI. This integration offers dual advantages, encompassing the multiscale characteristics of the SPI and the ability to measure the impact of temperature on drought of the PDSI. SPEI demonstrates robust applicability under complex climatic conditions (Potopová *et al.*, 2015; Chen *et al.*, 2023; Sun and Liu, 2019; Yao *et al.*, 2021).

However, previous studies on the spatiotemporal evolution of meteorological drought based on SPEI have primarily focused on the basin (Wang *et al.*, 2018b; Polong *et al.*, 2019), regional (Mehr and Vaheddoost, 2020; Gao *et al.*, 2017) or national scales (Wu *et al.*, 2020a, 2020b; Potopová *et al.*, 2015). Li *et al.* (2015a) analyzed drought in southwest China using SPEI and observed a notably decreasing trend in mean SPEI values at multiple scales. Yu *et al.* (2014) reported frequent and widespread drought occurrences in China over the past decades. In addition, Wang *et al.* (2015) pointed out the mitigation of drought conditions across the entire Huang-Huai-Hai Plain (32°~40°N, 114°~121°E) over the past 30 years. Precipitation and potential evapotranspiration (ET_0) are the two main factors affecting dry-wet climate changes (Vicente-Serrano *et al.*, 2015), and the selection of the ET_0 calculation method is crucial for SPEI estimation. Some scholars prefer Thornthwaite and Hargreaves equations (Wang *et al.*, 2015; Zarei and Mahmoudi, 2017). However, studies have confirmed that, besides temperature and precipitation, other factors such as wind speed (WIN), air pressure, relative humidity (RHU) and radiation also affect regional dry-wet conditions (Maček *et al.*, 2018). Considering the limitations of existing drought indices (SPI and PDSI), this study uses the Penman–Monteith (PM) formula to calculate SPEI and analyze the characteristics and periods of meteorological drought stage evolution.

Furthermore, the Mann-Kendall method has been used to detect abrupt changes in the phase segmentation and periodic evolution of drought (Jia *et al.*, 2018; Wang *et al.*, 2018c; Wu *et al.*, 2020b). In comparison with the Mann-Kendall method, the Bernaola-Galvan (BG) segmentation algorithm can segment nonstationary sequences into multiple stationary subsequences with varying mean values, where the scale of each stationary subsequence is adjustable (Wang *et al.*, 2018a). Although wavelet analysis has been used to identify the periodicity of drought (Wang *et al.*, 2018c), it fails in capturing the phasic change trend of drought (Wang *et al.*, 2018a). Consequently, the BG segmentation algorithm and extreme-point symmetric mode decomposition (ESMD) were introduced to divide the period and identify the phasic and periodic change trend of meteorological drought. As an important, sensitive and fragile environmental area of China, the ESAC is highly susceptible to global

climate change, significantly impacting the ecosystem with potentially irreparable consequences to a certain extent.

Therefore, by focusing on the ESAC as the case study area, this study used the PM formula and principles of energy balance to calculate the SPEI, thus exploring the multi-timescale changes of meteorological droughts. Furthermore, the BG algorithm and ESMD were used to analyze the phase and periodicity characteristics of drought change. In particular, the main objectives of this study are to:

- compare the multi-scale spatiotemporal changes in meteorological droughts between the ESAC and Chinese Mainland;
- identify variations in drought frequency and intensity in response to climate factors; and
- determine the periodic patterns of meteorological droughts.

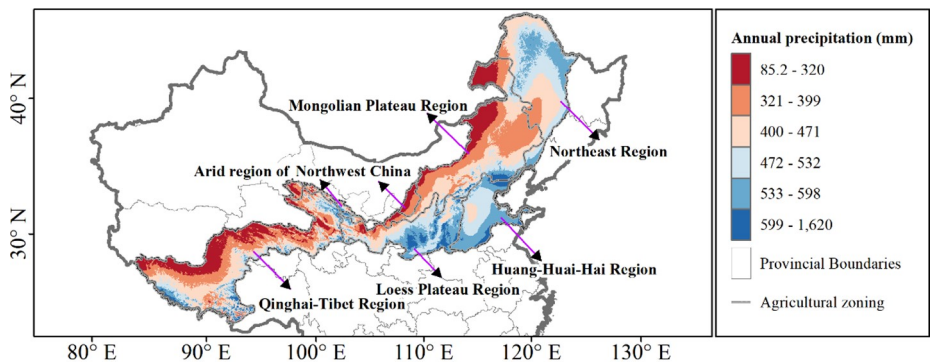
2. Materials and methods

2.1 Study area

The ESAC comprises a strip-like region, trending northeast to southwest, delineated by a 400 mm isohyet of China from 1961 to the present, with a guarantee rate of annual precipitation reaches 400 mm of 5% (northwest boundary) and 95% (southeast boundary) (Figure 1). Given the varied climatic and topographic backgrounds in the ESAC, as referenced from Zhong et al. (2019) and Wei et al. (2021), this study divided it into six regions with similar climatic conditions based on agricultural production conditions, characteristics and development direction. The specific partitions are as follows: northeast region (NER), Loess Plateau Region (LPR), Mongolian Plateau Region (MGR), Huang-Huai-Hai Region (HHHR), arid region of Northwest China (ANC) and Qinghai-Tibet Region (QTR).

2.2 Materials

Meteorological data, including average temperature, maximum temperature, minimum temperature, rainfall, RHU, WIN and sunshine duration (SSD), were collected from over 2,400 national meteorological observation stations across China. The number of meteorological stations in China was less than 200 between 1951 and 1960; however, it surged to more than 2,000 after 1961. Since then, the number has remained relatively constant. Therefore, to ensure



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Figure 1. Geographical location of the study area

improved interpolation accuracy, the research period for this study was set from 1961 onward. In addition, the meteorological data used in this study had a monthly temporal resolution.

2.3 Methods

First, from the perspective of agricultural zones, ET_0 was calculated using the PM formula, relying on climate indicators such as temperature (maximum, minimum and average), WIN, SSD and RHU observed at meteorological stations. Second, the spatial and temporal variations in drought at interannual, seasonal and monthly scales were analyzed using the SPEI. Third, the BG segmentation algorithm and ESMD were used to divide the research period and identify the period and trend characteristics of drought. In addition, drought frequency and intensity were analyzed using nonparametric trend analysis.

2.3.1 Standardized precipitation evapotranspiration index. In this study, various SPEI scales were used, including SPEI-1, SPEI-3, SPEI-6 and SPEI-12. SPEI-1 reflects drought on a monthly scale, SPEI-3 captures drought changes on a seasonal scale, SPEI-6 represents drought changes over a half-year period and SPEI-12 reflects interannual drought changes. The steps for calculating SPEI at different time scales are outlined below:

- The difference between the monthly recorded precipitation and ET_0 calculated using the Food and Agriculture Organization (FAO) PM equation (Allen *et al.*, 1998) represents the climatic water balance, indicating either a water surplus or deficit (Vicente-Serrano *et al.*, 2010). It is calculated as follows:

$$D_j = P_j - ET_j \quad (1)$$

where D_j represents the water deficit in month j , P_j stands for the precipitation in the first month and ET_j denotes the potential evapotranspiration in the first month.

- Cumulative water deficit sequences at different time scales were established according to linear decreasing weight schemes:

$$\begin{cases} X_{i,j}^k = \sum_{l=13-k+j}^{12} D_{i-1,l} + \sum_{l=1}^j D_{i,l} & j < k \\ X_{i,j}^k = \sum_{l=j-k}^j D_{i,l} & j \geq k \end{cases} \quad (2)$$

where $X_{i,j}^k$ represents the accumulated water deficit in month j of year i and $D_{i,l}$ denotes the water deficit in month j of year i .

- As the original cumulative water deficit typically exhibits negative values, it is necessary to introduce a log-logistic probability distribution function to calculate the probability distribution of the cumulative water deficit. The log-logistic probability distribution function is calculated as follows:

$$F(\mathbf{X}) = \left[1 + \left(\frac{\alpha}{X - \gamma} \right)^\beta \right]^{-1} \quad (3)$$

where α , β and γ indicate the scale, shape and position, respectively, and are calculated as follows:

$$\beta = \frac{2w_1 - w_0}{(6w_1 - w_0 - 6w_2)} \leftarrow \quad (4)$$

$$\alpha = \frac{(w_0 - 2w_1)\beta}{\Gamma(1 + 1/\beta)\Gamma(1 - 1/\beta)} \leftarrow \quad (5)$$

$$\gamma = w_0 - \alpha\Gamma(1 + 1/\beta)\Gamma\left(1 - \frac{1}{\beta}\right) \quad (6)$$

$$w_s = \frac{1}{n} \sum_{q=1}^n \left(1 - \frac{q-0.35}{n}\right)^s X_q \quad (7)$$

where w_s represents the probability weight moment for $s = 0, 1$ or 2 , q is the ordinal number of the cumulative water deficit in ascending order, where $X_1 \leq X_2 \leq \dots \leq X_n$, and $\Gamma(\beta)$ denotes the gamma function.

- The probability distribution of the cumulative water deficit series for each month, $F(X)$, was normalized, where p is the probability of $X_{i,j}^k$:

$$p = 1 - F(X) \quad (8)$$

If $p \leq 0.5$, $w = \sqrt{-2\ln p}$,

$$SPEI = w - \frac{C_0 + C_1w + C_2w^2}{1 + d_1w + d_2w^2 + d_3w^3} \quad (9)$$

If $p > 0.5$, $w = \sqrt{-2\ln(1-p)}$,

$$SPEI = \frac{C_0 + C_1w + C_2w^2}{1 + d_1w + d_2w^2 + d_3w^3} - w \quad (10)$$

where $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$ and $d_3 = 0.001308$.

2.3.2 Quantitative characterization of drought. **2.3.2.1 Drought frequency.** Drought is identified from SPEI according to the classification standard outlined in [Table 1](#). Drought frequency refers to the ratio of drought years to the total number of years within a specific regional unit since the beginning of the record, effectively indicating the occurrence rate of drought events over a certain period. It is calculated as follows:

$$F_i = \frac{n}{N} \times 100\% \quad (11)$$

where F_i represents the drought frequency, i denotes the meteorological station, n signifies the years with drought events and N indicates the total number of years. The frequency of drought at both annual and seasonal scales was calculated in this study.

Table 1. Classification standard of standardized precipitation evapotranspiration index drought grade

Categorization	Not dry	Mild drought	Moderate drought	Severe drought	Extreme drought
SPEI values	$-0.5 < \text{SPEI}$	$-1.0 < \text{SPEI} \leq -0.5$	$-1.5 < \text{SPEI} \leq -1.0$	$-2.0 < \text{SPEI} \leq -1.5$	$\text{SPEI} \leq -2.0$

Source: Wang *et al.* (2021)

2.3.2.2 Drought intensity. Drought intensity is determined by the absolute value of the average SPEI accumulation during the drought period. The formula for drought intensity is as follows (Wang *et al.*, 2018a):

$$I = \left| \frac{1}{n} \sum_{i=1}^n \text{SPEI}_i \right| \quad (12)$$

where I represents the drought intensity, n stands for the drought frequency and SPEI_i indicates the SPEI value at the time of drought occurrence.

2.3.2.3 Drought station ratio. The drought station ratio is the percentage of drought-affected stations within a specific regional unit. This ratio represents the drought impact range over a certain period and indirectly reflects the severity of the drought. It is calculated as follows:

$$P_j = \frac{m}{M} \times 100\% \quad (13)$$

where P_j represents the drought station ratio, M is the total number of weather stations in the study area and m is the number of drought-affected stations in year j .

In this study, SPEI was calculated for various time scales using the PM formula recommended by the FAO (Allen *et al.*, 1998). The criteria for classifying drought grade based on SPEI (Table 1) were determined based on the actual drought conditions in the study area and those reported by Wang *et al.* (2021).

2.3.3 Geodetector method. Considering the significant correlation between climate factors and drought occurrences, this study employs the Geodetector method to assess the extent to which climate factor X_s explains attribute Y . In addition, it evaluates whether the combined influence of X_1 and X_2 increases or decreases the explanatory capacity of the dependent variable Y (Wang and Xu, 2017). The expression is as follows:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} = 1 - \frac{SSW}{SST}$$

$$SSW = \sum_{h=1}^L N_h \sigma_h^2, \quad SST = N \sigma^2$$

where $h = 1, \dots, L$ represents the stratification of variable Y or factor X , indicating classification or partition. N_h and N denote the number of units in layer h and the entire region, respectively. σ_h^2 and σ^2 are the variances of the Y values for layer h and the entire

region, respectively. SSW and SST denote within sum of squares and total sum of squares, respectively. The range of q is $[0, 1]$. A higher q value indicates stronger explanatory power of the independent variable X for attribute Y , whereas a lower value suggests the opposite.

The Q -value transformation conforms to the noncentral F -distribution:

$$F = \frac{N-L}{L-1} \frac{q}{1-q} \sim F(L-1, N-L; \lambda)$$

$$\lambda = \frac{1}{\sigma^2} \left[\sum_{h=1}^L \bar{Y}_h^2 - \frac{1}{N} \sum_{h=1}^L \sqrt{N_h} \bar{Y}_h \right]^2 \left(\right)$$

where λ serves as a noncentral parameter and $\bar{Y}_h$ represents the mean of layer h . According to the above formula, the significance of the q value can be tested.

2.3.4 Bernaola-Galvan segmentation method. Bernaola-Galvan (2001) initially applied a heuristic segmentation algorithm in the medical field, and subsequently, its utilization has extended to climatology and geography (Qin et al., 2011). The BG mutation detection and segmentation method are not constrained by data limitations. In addition, it divides nonstationary sequences into multiple stationary subsequences based on a t -test (Wang et al., 2018a). Based on the introduction of the BG segmentation algorithm, this research uses it for detecting mutation years in SPEI time series. Subsequently, the characteristics of phase changes in meteorological drought were analyzed. For the time series $X(t)$, the BG algorithm equations are as follows:

$$T(i) = \left| \frac{\mu_1(i) - \mu_2(i)}{S_D(i)} \right| \leftarrow \quad (14)$$

$$S_D(i) = \left[\frac{(N_1 - 1) \times s_1(i)^2 + (N_2 - 1) \times s_2(i)^2}{N_1 + N_2 - 2} \right]^{1/2} \times \left[\frac{1}{N_1} + \frac{1}{N_2} \right] \quad (15)$$

where $S_D(i)$ represents the combined deviation of i points and N_1 and N_2 denote the left and right points, respectively. $\mu_1(i)$ and $\mu_2(i)$ signify mean deviation, whereas $s_1(i)$ and $s_2(i)$ indicate standard deviation to the left and right of each point.

2.3.5 Nonparametric trend analysis. Sen's (1968) slope estimation method was used to calculate the slope (β) of the long-term climate time series, thereby capturing the change rates and trends over the duration of time (Li et al., 2022; Noshadi and Ahani, 2015). For the time series $x_t = (x_1, x_2, x_3, x_4, \dots, x_n)$, Sen's slope equation is given as:

$$\beta = \text{Median}(x_j - x_i / j - i), v_j > i \quad (16)$$

where x_i and x_j represent the sample data value and β denotes the median slope of the combined time series data.

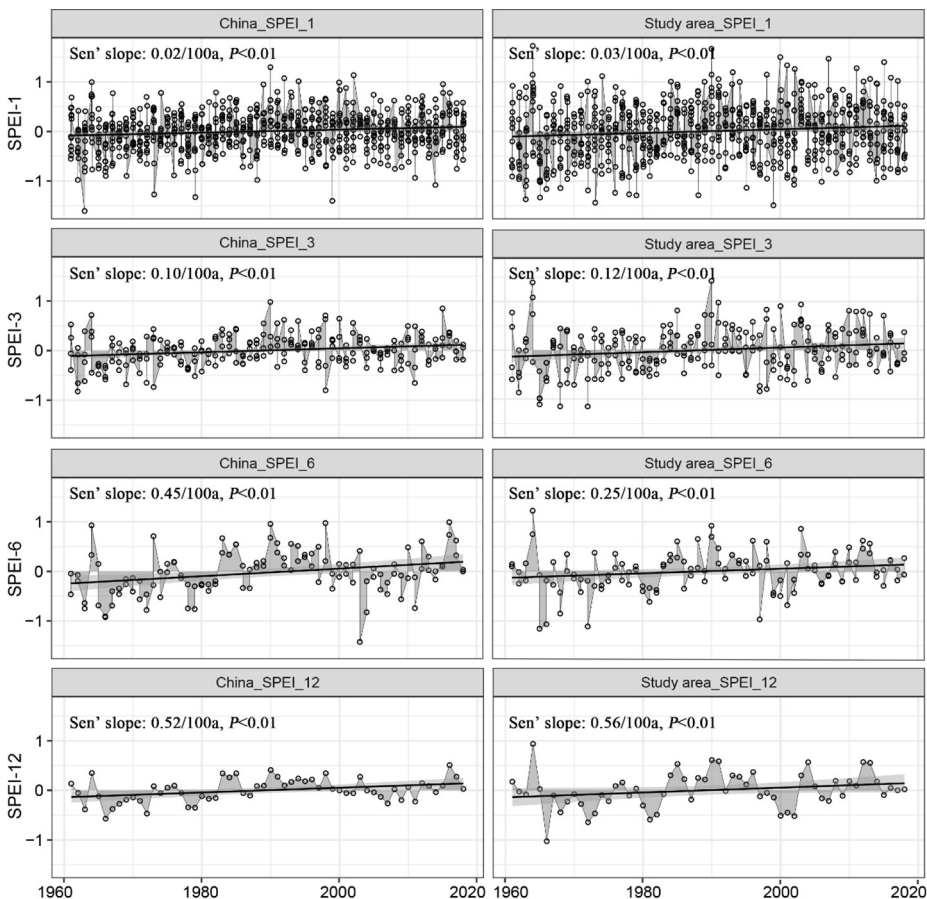
2.3.6 Extreme-point symmetric mode decomposition. ESMD represents the latest advancement in empirical mode decomposition, aimed at solving the problem of "mode superposition". It efficiently detects large-scale cyclic periods and nonlinear trends, stabilizing the signal and extracting periodic oscillations and trend components from the original data.

Moreover, it yields several intrinsic mode functions (IMF) corresponding to different periods and real trend components (Wang and Li, 2013). ESMD has been applied in atmospheric science, ecology, geography and other fields (Li et al., 2013; Wang et al., 2014; Feng and Su, 2019). In this study, the ESMD method was used to decompose the time-frequency period and trend of the SPEI sequence, enabling an analysis of the periodic characteristics of SPEI.

3. Results

3.1 Time variation characteristics of standardized precipitation evaporation index

3.1.1 Time variation characteristics of standardized precipitation evaporation index at different time scales. Figure 2 shows that the number of mild drought years ($-1.0 < \text{SPEI-12} \leq -0.5$) in the study area was significantly higher than in mainland China. Mild droughts were observed in 1966 in mainland China, whereas in the study area, mild droughts were

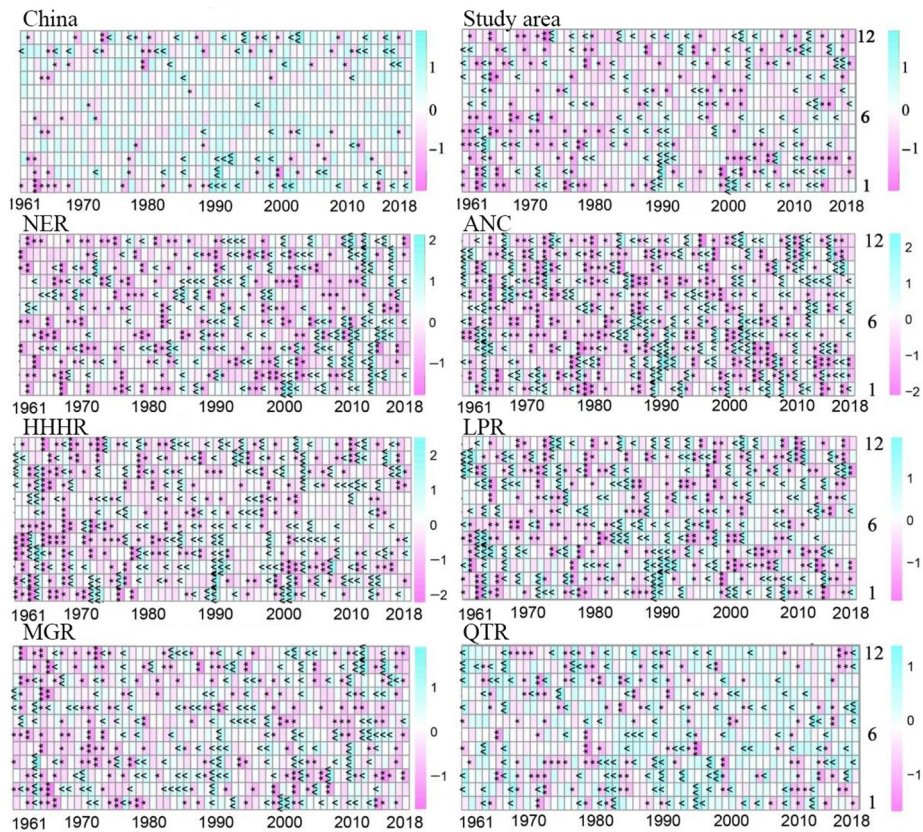


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Figure 2. Temporal variation of SPEI at different time scales in China and the study area

recorded in 1972, 1981, 2000 and 2002. Furthermore, a moderate drought occurred in the study area in 1966 (−1.03). The trend analysis reveals varying rates of SPEI increase across time scales in both regions. Moreover, the rate of increase positively correlates with the time scale of SPEI, with SPEI-12 exhibiting the highest rate, followed by SPEI-6 and SPEI-3, whereas SPEI-1 shows the lowest rate. The increasing rates, drought grades and the number of drought years for SPEI-12 ($0.56 \times 10^{-2} \text{ yr}^{-1}$, $p < 0.05$), SPEI-3 ($0.12 \times 10^{-2} \text{ yr}^{-1}$, $p < 0.01$) and SPEI-1 ($0.03 \times 10^{-2} \text{ yr}^{-1}$, $p < 0.01$) in the ESAC were higher than those in mainland China. Moreover, although the northwest of China shows a wet trend, the southwest demonstrates an intensifying drought trend.

3.1.2 *Distribution characteristics of monthly meteorological drought.* The distribution of SPEI-1 in different regions (Figure 3) reveals a notably higher SPEI in mainland China



Notes: *** stands for $-2.0 < \text{SPEI} \leq -1.5$, ** indicates $-1.5 < \text{SPEI} \leq -1.0$, * indicates $-1.0 < \text{SPEI} \leq -0.5$, ^^ stands for $1.5 < \text{SPEI} \leq 2$, ^^ stands for $1 < \text{SPEI} \leq 1.5$, ^ stands for $0.5 < \text{SPEI} \leq 1$

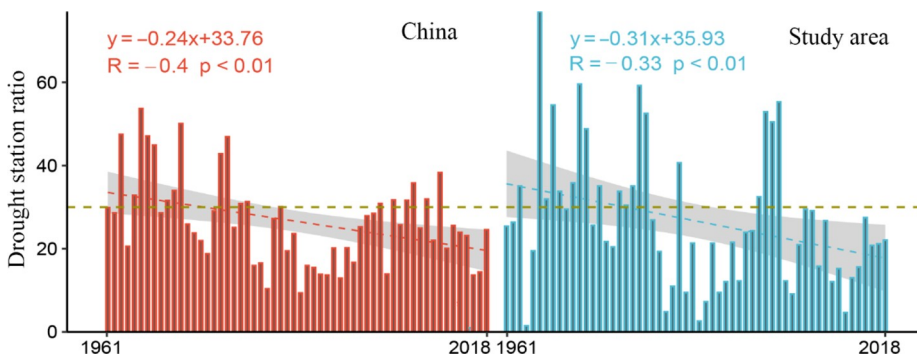
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Figure 3. Distribution characteristics of SPEI-1 in the Chinese Mainland (a) and research area (b)

compared to the ESAC. This indicates that the climate in China is more humid than that in the study area. Furthermore, drought occurrences of all grades were more frequent in the study area than in mainland China. The probability of mild drought events in China was highest in January, November, and December (15.52%) and lowest in July and August (1.72%). Since the 1960s, drought occurrences in the study area have been significantly more frequent than in mainland China. Consequently, it can be inferred that the study area poses a significantly higher risk of drought events than mainland China.

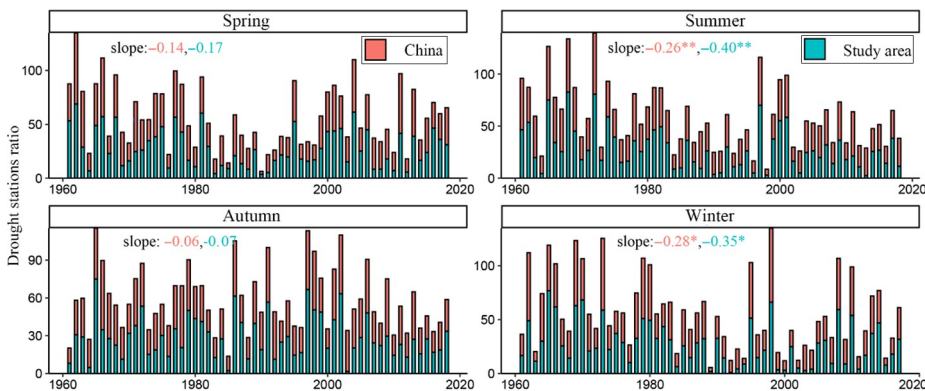
3.1.3 Temporal variation of drought stations ratio. **3.1.3.1** Variations in annual drought station ratios. The drought station ratio serves to delineate the extent of drought events. [Figure 4](#) shows that the average drought station ratios in the Chinese Mainland and the study area were 26.56% and 26.67%, respectively. In China, seven years exhibited drought station ratios exceeding 40%, notably peaking at 53.66% in 1966 and 50.08% in 1972. Conversely, in the study area, the drought station ratio exceeded 40% for 10 years and reached 50% for eight years. The highest drought station ratio (76.99%) was observed in 1966, corresponding to an SPEI-12 value of -1.03 . Both mainland China and the study area witnessed a significant decrease in annual drought station ratios, with decreasing rates of -0.24 and -0.31 yr^{-1} , respectively. The interannual variation in drought station ratios exhibited distinct phase characteristics in both regions. Notably, there was a substantial decline in the drought station ratio from the 1960s to the 1990s, followed by an increasing trend since the 1990s.

3.1.3.2 Variation in seasonal drought station ratio. Similarly, the seasonal drought station ratio was calculated for both China and the study area ([Figure 5](#)). The study area exhibited a higher number of years with drought station ratios higher than 60% and lower than 10% in spring, summer and autumn compared to mainland China. Conversely, the study area had fewer years with drought station ratios lower than 10% in winter than China, indicating more pronounced fluctuations in the drought station ratio in spring, summer and autumn compared to winter. The overall seasonal drought station ratio decreased in China as well as the study area, with a more significant decrease observed in the study area. In China, the most substantial decrease in drought station ratio occurred in winter (-0.28 yr^{-1} , $p < 0.05$), followed by summer (-0.26 yr^{-1} , $p < 0.01$). Furthermore, the highest decreasing rate of the drought station ratio was observed in summer (-0.40 yr^{-1} , $p < 0.01$), followed by winter (-0.35 yr^{-1} , $p < 0.05$).



Source: Created by authors

Figure 4. Temporal variation of annual drought station ratio in China and the study area



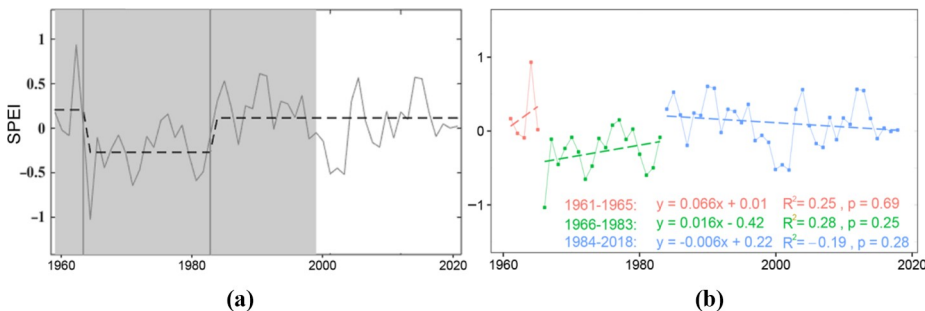
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Figure 5. Temporal variation of seasonal drought stations ratio in China and the study area

3.2 Characteristics of phase changes in meteorological drought

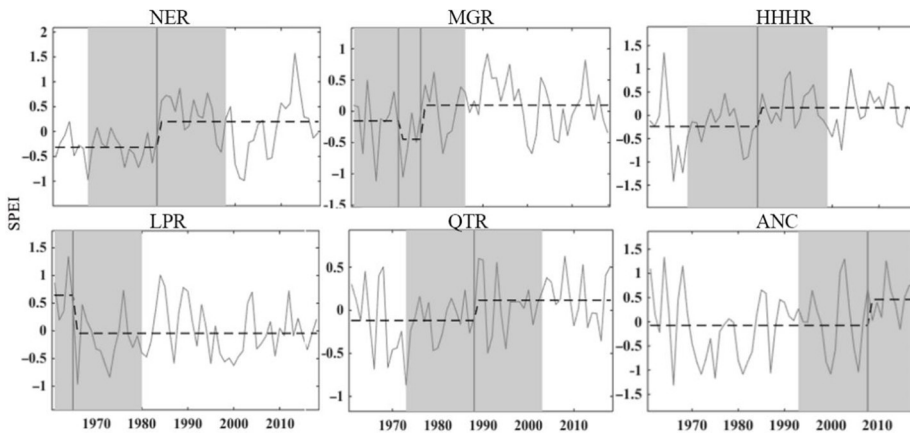
3.2.1 In the study area. In this study, the BG segmentation algorithm was used to segment the SPEI-12 sequence and explore the characteristics of its periodic changes. The parameters for the segmentation algorithm were defined as follows: the minimum segmentation length was set to 16 and the significance level was established at 0.95. The results showed two cumulative mutations of SPEI-12 in the study area, occurring in 1965 and 1983. The SPEI-12 changes were categorized into three phases: 1961–1965, 1966–1983 and 1984–2018 [Figure 6(a)]. Furthermore, Figure 6(b) illustrates that the mean SPEI values during these phases were 0.21, -0.27 and 0.12, respectively. Their corresponding linear change rates were 0.066, 0.016 and -0.006 yr⁻¹.

3.2.2 In different regions. 3.2.2.1 Segmentation of drought changes in different regions. There were significant differences in geographical location, hydrothermal conditions and topography across different regions. In addition, drought events exhibited clear spatial and temporal heterogeneity. As depicted in Figure 7, the BG segmentation algorithm was used to segment the SPEI-12 of the six regions. The results revealed that NECR, HHHR, LPR, ANC



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Figure 6. (a) Stage segmentation of SPEI-12 sequence in the study area and (b) its variation characteristics

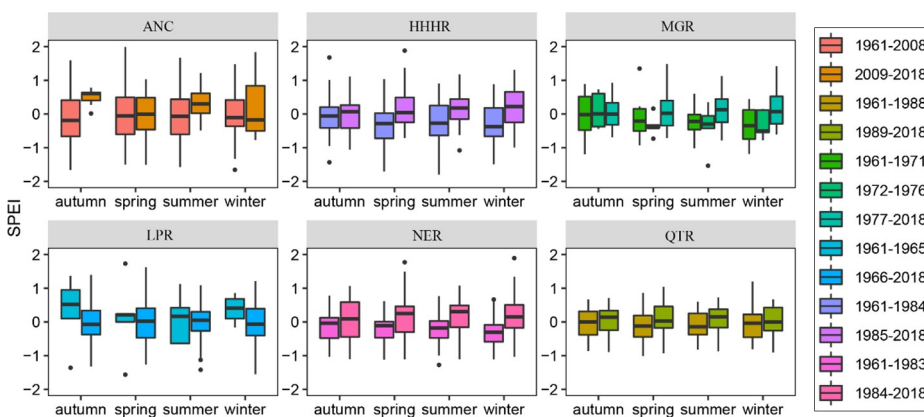


Source: Created by authors

Figure 7. Stage segmentation of SPEI-12 sequence in different regions

and QTR each had a singular mutation, corresponding to the years 1983, 1984, 1965, 2008 and 1988, respectively. Conversely, MGR exhibited two mutations in 1971 and 1976.

3.2.2.2 Distribution characteristics of SPEI-3 in different regions during different time periods. **Figure 8** shows the variation in SPEI-3 across different regions during distinct time periods. In HHHR, NER and QTR, SPEI-3 exhibited lower values in the first period compared to the second period, indicating a reduction in drought severity and a transition toward a wetter climate. In contrast, in LPR, SPEI-3 was significantly higher in the first period than in the second, indicating a continuous increase in drought conditions. In terms of seasonal changes, ANC displayed a trend towards aridity in winter but a gradual shift towards humidity in spring, summer and autumn. In MGR, SPEI-3 exhibited a U-shaped pattern in all seasons except autumn, indicating a transition from wet to dry and back to wet climatic conditions.

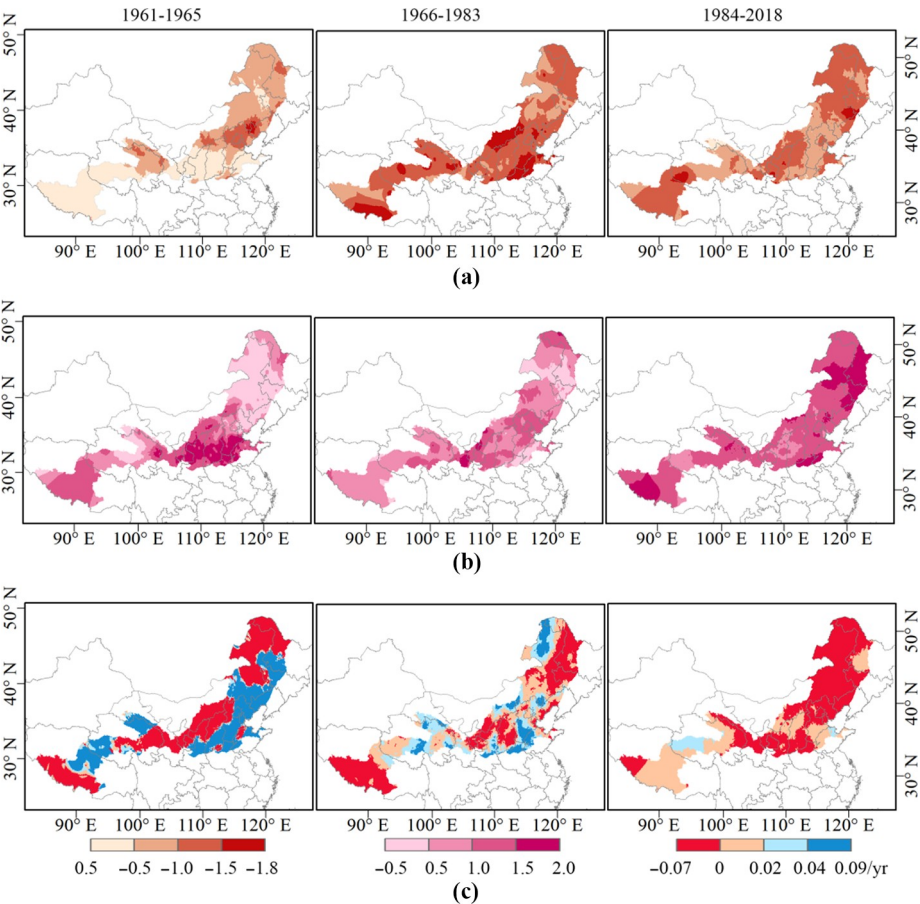


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Figure 8. Distribution characteristics of SPEI-3 in the study area during different time periods

3.3 Drought pattern evolution

3.3.1 Evolution of annual SPEI patterns in different time periods. To illustrate the spatial pattern characteristics of SPEI-12, this study extracted both the minimum [Figure 9(a)] and maximum values [Figure 9(b)] of SPEI-12 at the pixel scale in the study area during the three time periods. This approach aimed to characterize both the dry and wet conditions prevailing in the region. Analysis of the minimum SPEI-12 values revealed an increasing trend in drought severity, with the lowest value observed during the first period from 1961 to 1965, the highest between 1966 and 1983 and the second highest from 1984 to 2018. In contrast, the maximum SPEI-12 values were highest from 1961 to 1965, lowest between 1966 and 1983 and second lowest from 1984 to 2018. Examining the interannual variation in SPEI-12 at different time periods [Figure 9(c)], the largest range of variation occurred from 1961 to



Notes: (a); (b) represent the minimum and maximum values of SPEI-12, respectively;
(c) represents the changing trend of SPEI-12
Source: Created by authors

Figure 9. Change characteristics of SPEI-12 patterns

1965. Notably, significant upward variation (—four to nine per century) was mainly observed in regions west of the Heilongjiang, Jilin and Liaoning provinces, the North China Plain and parts of the Qinghai–Tibet Plateau. Conversely, areas experiencing decreasing SPEI-12 variation were located in the northeast of Inner Mongolia, northwest of the Loess Plateau and south of Tibet. From 1984 to 2018, the regions with decreasing variation were mainly distributed in the central and northern parts of the study area, whereas the southern region exhibited a slight increase. It should be noted that since 1961, there has been a gradual expansion of the area experiencing ascending SPEI-12 values on the Tibetan Plateau, indicating a trend toward climatic wetting. In contrast, the trend toward aridification was evident in the northeastern region of the study area.

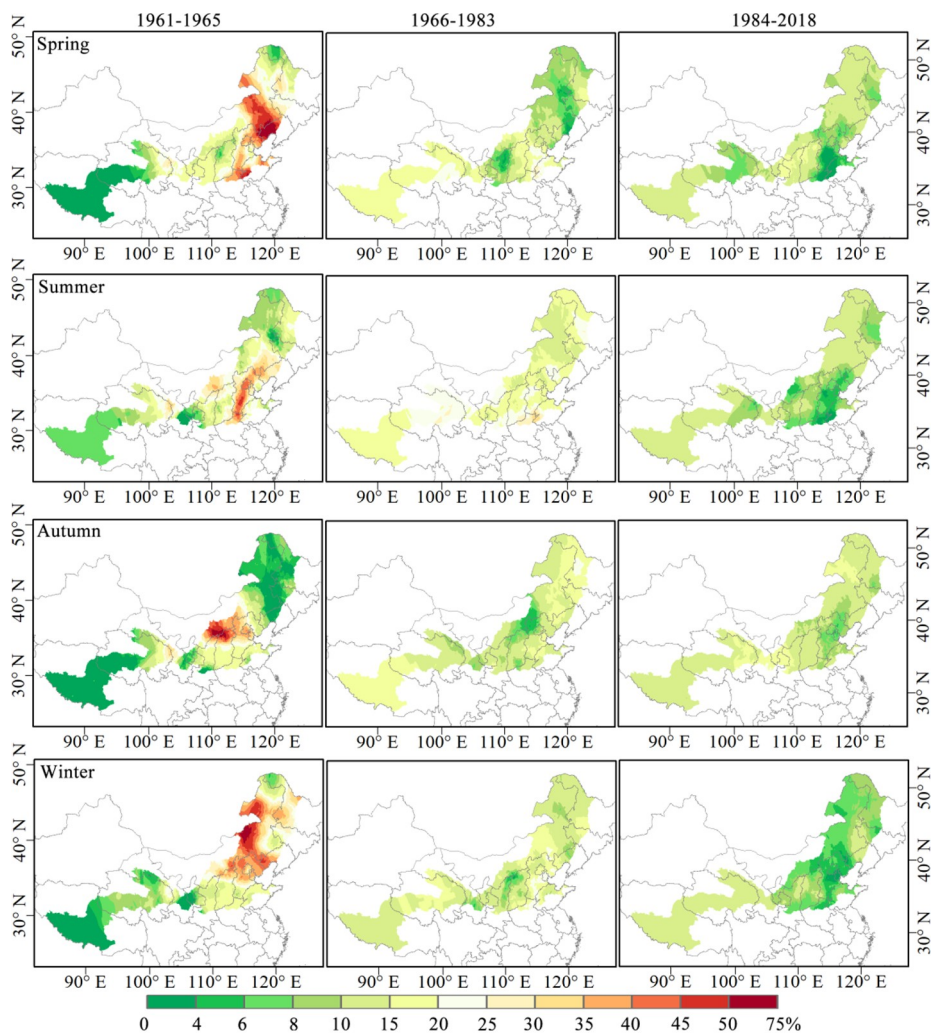
3.3.2 Drought frequency and intensity in different seasons. Compared to mild drought, moderate and severe drought events pose greater risks to nature, human production and life. Therefore, based on the results of BG segmentation, this study analyzed the temporal and spatial evolution characteristics of moderate and severe drought occurrences in the study area. Three periods were examined: 1961–1965, 1966–1983 and 1984–2018:

- Spatial distribution of moderate and severe drought frequency

The spatial distribution of moderate and severe drought frequency in the study area varied across different periods and seasons. For example, during the period from 1961 to 1965, regions experiencing moderate and severe drought frequencies exceeding 50% in spring were mainly distributed in Liaoning and Inner Mongolia. In summer, a belt extending north of Henan through Hebei and Beijing, connecting to Inner Mongolia (Figure 10), exhibited pronounced drought occurrences. In addition, these events were concentrated in the border areas of Inner Mongolia, Shaanxi, Shanxi and Hebei in autumn, and in northeast Inner Mongolia, north Hebei and southwest Liaoning in winter. From 1966 to 1983, the frequency of moderate to severe drought events peaked (over 15%) in summer, primarily observed in the border areas of Qinghai, Henan, Hebei and Shanxi. Conversely, drought occurrences in spring were less frequent in northeast China. Between 1984 and 2018, the frequency of moderate to severe drought events was relatively high in autumn, followed by summer and spring, mainly distributed in Beijing, Tianjin, Henan and Shandong. The occurrence of drought events during winter was highest (<10%) in areas encompassing Beijing, Tianjin, Hebei, Shandong, Henan, Inner Mongolia, Heilongjiang and western Jilin.

- Spatial distribution of moderate and severe drought intensity

Regional and seasonal changes in the intensity of moderate and severe drought during different periods were observed in the study area (Figure 11). From 1961 to 1965, areas experiencing high drought intensities (above 1.5) during spring and autumn exhibited consistent spatial distributions. These areas were primarily concentrated in two regions: a collective region encompassing Gansu, Ningxia, Shaanxi, Shanxi, southern Hebei, Shandong and northern Henan, and the border area of Hebei, Liaoning, Jilin and Inner Mongolia. High-intensity values in summer and winter were mainly observed in the North China Plain and the northern Loess Plateau. During the summers from 1966 to 1983, the anticipated high drought intensity of moderate or severe drought events was widespread, particularly in northern Shanxi, central, southern and northeastern Hebei, western Jilin and northern Shandong. In spring, areas with the lowest frequency values (below 1.0) comprised the largest proportion and were predominantly found in northeast Inner Mongolia, north Shaanxi and northwest Shanxi. Conversely, in winter and autumn, regions with the lowest frequency values were mainly distributed across Shaanxi, north Shanxi, northwest Hebei and southeast Inner Mongolia. From 1984 to 2018, areas with low drought frequency values accounted for the



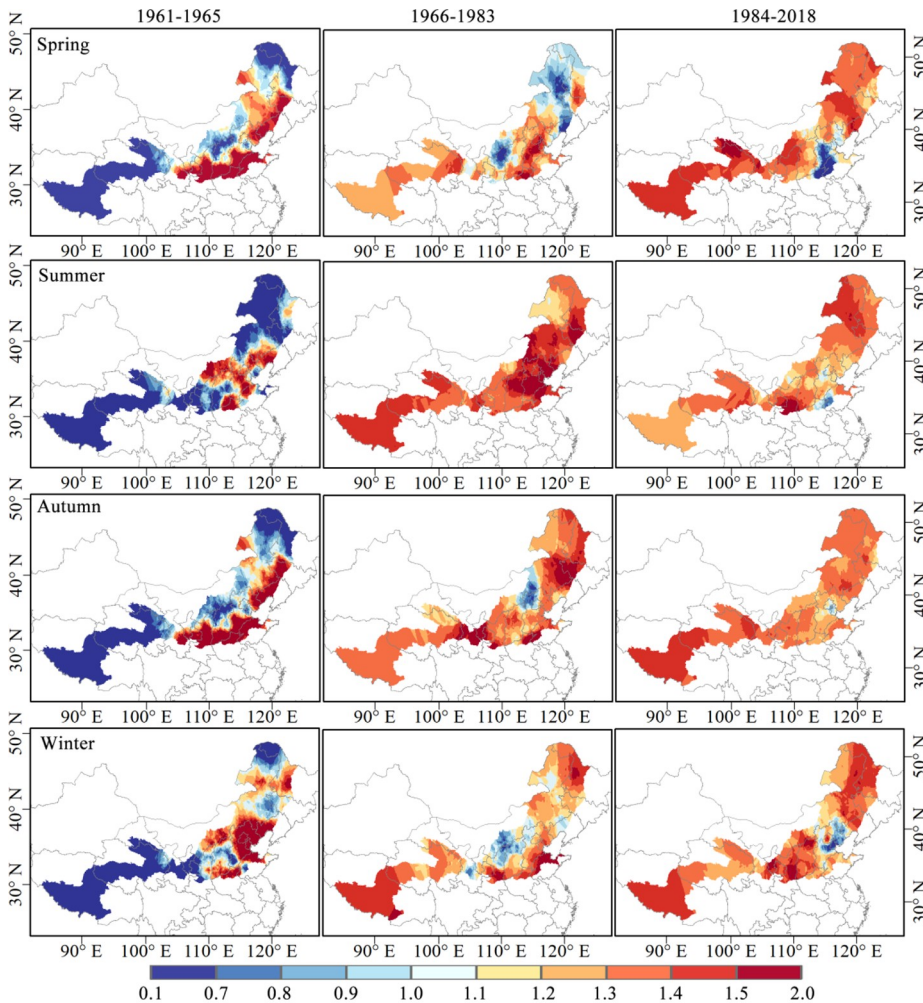
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Figure 10. Spatial distribution of moderate and severe drought frequency in different periods

largest proportion of the area, mainly distributed in central, southern and northeastern Hebei, Henan and Shandong. Drought intensity in spring, summer and winter exceeded that in autumn in the northeastern regions of Inner Mongolia.

3.4 Effects of climate variables and their interactions on drought

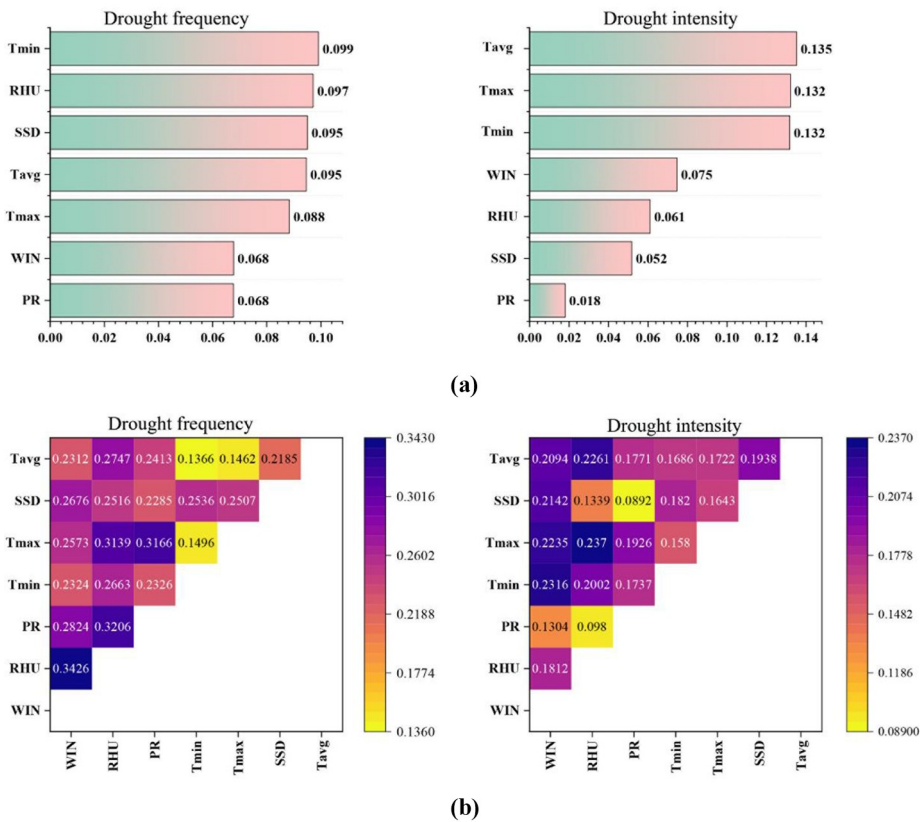
First, based on the long-term meteorological data from stations in the study area, the geographical detector method was used to measure the influence of climate explanatory factors and their interaction on drought occurrences. This involved assessing the contribution of



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Figure 11. Spatial distribution of moderate and severe drought intensity in different periods

different climatic factors such as temperature, humidity WIN and SSD to moderate and severe drought events. The results (Figure 12) showed that moderate and severe drought frequency was mainly affected by minimum temperature (Tmin) and RHU, whereas moderate and severe drought intensity was mainly regulated by maximum temperature (Tmax), Tmin and average temperature (Tavg), with Tavg being the most significant. In addition, the effects of pairwise interactions among these climate variables on both the frequency and intensity of moderate and severe droughts were analyzed. It was revealed that the interaction between RHU and WIN exhibited the most notable influence on drought frequency, followed by the interaction between RHU and precipitation. Conversely, the influence of temperature interactions on drought



Notes: (a) Factor detector; (b) interaction detector

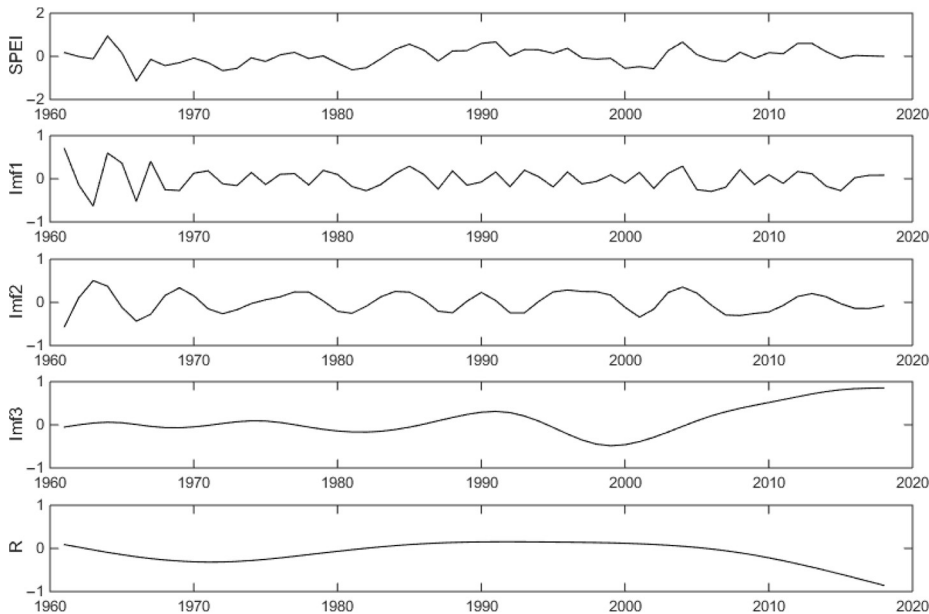
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Figure 12. Analysis of the influence of climate factors on drought

frequency was generally low. However, interactions involving temperature and WIN, or temperature and RHU, could significantly affect drought intensity.

3.5 Decomposition of drought periods and trends based on extreme point symmetric mode decomposition

3.5.1 Drought periods and trend decomposition. In this study, the ESMD method (Li *et al.*, 2013; Feng and Su, 2019) was used to decompose the SPEI-12 sequences in the study area over the entire study period. Subsequently, three IMF components and a trend term R were obtained to analyze the long-term trend and periodic change characteristics of the SPEI sequences (Figure 13). As shown in Table 2, the main periods of the IMF1, IMF2 and IMF3 components determined based on fast Fourier transform were 3.1, 7.3 and 29 years, respectively. These results indicate that interannual drought exhibits quasi-three-year and quasi-seven-year periodic characteristics, along with quasi-29-year cyclical characteristics of interdecadal drought. The variance contribution rate represents the importance of each IMF



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Figure 13. IMF components and trend term R of SPEI-12 in the study area

Table 2. Periodicity, variance contribution rate and correlation coefficient of IMF components in SPEI-12 series

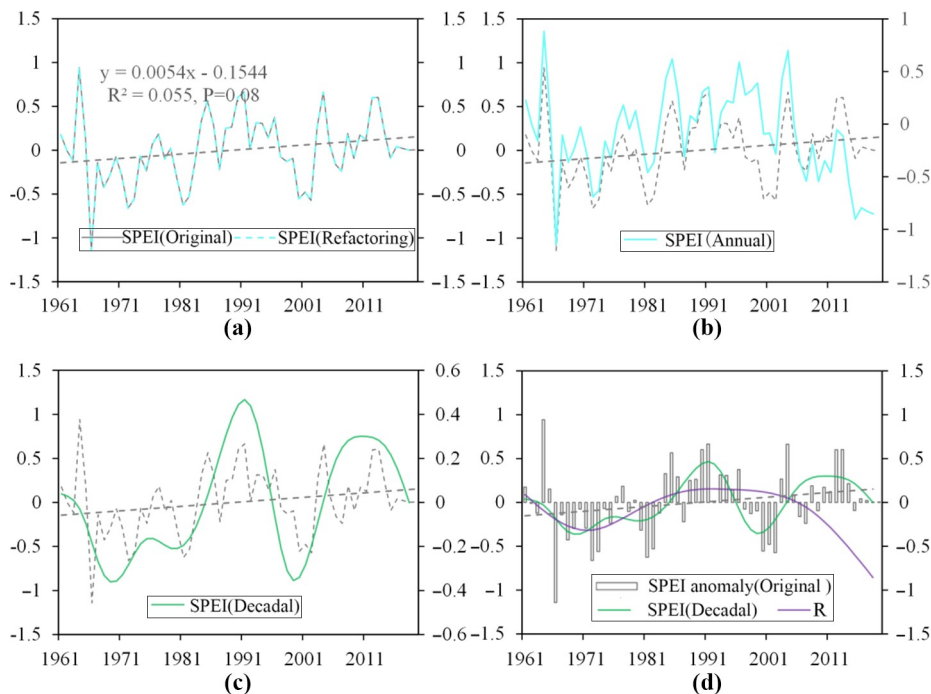
IMF	IMF1	IMF2	IMF3	Trend term R
Primary period	3.1	7.3	29	
Variance contribution rate (%)	43.25	26.97	21.92	7.87
Correlation coefficient	0.57**	0.47**	0.32*	0.12

Notes: ** Means significant at 0.01 level; * means significant at 0.05 level

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component in the original sequence. IMF1 displayed prominent oscillations, with the largest quasi-three-year variance contribution rate (43.25%). This was followed by a quasi-seven-year period of IMF2 (26.97%), indicating that interannual oscillations (3.1 and 7.3 years) played a dominant role in the SPEI sequence variability. Assessing the correlation between each IMF mode and the original SPEI-12 sequence, the first mode exhibited the highest correlation coefficient (0.57), followed by the second mode (0.47) and the third mode (0.32).

3.5.2 DSMD applicability analysis. IMF1, IMF2, IMF3 and R were used to reconstruct the SPEI sequence, aiming to verify the reliability of ESMD. As depicted in Figure 14(a), the reconstructed and original SPEI sequences exhibit nearly perfect alignment, confirming the credibility of ESMD. In Figure 14(b), the interannual SPEI from the ESMD decomposition is compared with the original SPEI sequence. The decomposed SPEI represents the cumulative value of



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Figure 14. Verification of SPEI-12 results based on ESMD

the interannual IMF1 and IMF2, as well as the trend term R, which was obtained by filtering out large-scale oscillations. Furthermore, ESMD was used to characterize the interannual variation in SPEI, displaying a consistent trend with the original SPEI sequence and accurately depicting its temporal fluctuations. This confirms the dominant role of interannual oscillations in SPEI-12 changes in the study area. The decadal variation trend of the reconstructed SPEI was consistent with that of the original sequence, portraying the fluctuations in SPEI during the study period but with significantly lower accuracy compared to the interannual scale [Figure 14(c)]. In addition, Figure 14(d) shows that, in contrast to the original SPEI anomaly sequence, the decadal variation of the SPEI reconstructed by the ESMD components and the decomposition trend R exhibit a diminished ability to capture the SPEI changes that occurred.

4. Discussion

4.1 Phasic and periodic trends of dry and wet conditions

The examination of SPEI time-series variations across multiple scales (Figure 1) reveals that SPEI-1, without the influence of early meteorological conditions, is mainly affected by short-term meteorological changes, exhibiting the highest frequency of fluctuations, followed by SPEI-3 and SPEI-6. This is consistent with Seiler et al.'s (2002) earlier observation that SPEI time scales are negatively correlated with sensitivity to single or short-term weather fluctuations. As the 1960s, SPEI has shown an increasing trend in both mainland China and

the study area. Similar changes have been observed in the arid and semi-arid regions of northern China (Liu *et al.*, 2010; Jia and Zhang, 2020) and northwest China (Zhang *et al.*, 2020). Similarly, based on SPEI_{PM} results, Wang *et al.* (2015) found that drought risks decreased in the Huang Huai-Hai Plain between 1961 and 2010. Mohammad *et al.* (2013) reported a significant decrease in droughts during the vegetation-growing season in Inner Asia from the 1980s to the mid-1990s, followed by a significant increase since the mid-1990s, particularly evident in Xinjiang since the 21st century (Yao *et al.*, 2021). However, Zhou *et al.* (2020) predicted a drying trend in northeast China in forthcoming years, whereas drought events are gradually increasing in the Yellow River Basin, the Hai River Basin and the Southwest River Basins (Zhou *et al.*, 2021). The western regions of North China Plain, Loess Plateau, Sichuan and Yunnan-Guizhou Plateau are witnessing a notable aridification trend (Xu *et al.*, 2015). Yang *et al.* (2020) reported a prevalent drying trend in southwestern Canada during the winters from 1950 to 2016. These findings underscore spatiotemporal differences in the evolution of meteorological drought, affected by climate change, topography, soil texture and human activity.

The interannual variation of SPEI in the study area was characterized by significant spatial heterogeneity (Figure 9). Northeast China exhibits a pronounced trend toward aridity, whereas the Qinghai–Tibet Plateau experiences increasing humidity, consistent with previous research findings (Shi *et al.*, 2007, 2014; Liu *et al.*, 2016, 2013). Ma *et al.* (2020) proposed that drought patterns in northwest China from 1961 to 2017 align with global trends, characterized by prolonged duration and intense severity. Li *et al.* (2015b) conducted an evaluation of dry-wet conditions in China in recent decades using SPI, highlighting a trend towards increasing wetness in northwest China and growing aridity in northeast China. Wen *et al.* (2020) proposed SPEI drought trends on an annual scale from 2006 to 2100, indicating a wetting trend in northwest China under the RCP 26 scenario, with an increase of 0.005 per decade from January to August, whereas other regions experience aridification. Northwest and southeast China, however, exhibit a wetting trend from October to December, with a rate of 0.005 per decade. Chen *et al.* (2015b) concluded that precipitation on the Qinghai–Tibet Plateau has shown an overall upward trend in recent years, with annual precipitation rising at a rate of 2.2% per decade. Conversely, precipitation in north China, northeast China and southwest China has shown a decreasing trend (Ma *et al.*, 2015).

According to the time-series analysis of drought severity, both the interannual and seasonal drought station ratios in China and the study area showed a decreasing trend. These results are consistent with the observed trends in drought station ratios in northern China as reported by Hu *et al.* (2018). Similarly, aligning with the results obtained by Chen and Sun (2015), Figures 10 and 11 indicate that severe meteorological droughts at the seasonal scale were most prevalent during the 1960s in the ESAC. This is consistent with the historical occurrence of large-scale drought disasters in China from the late 1950s to the early 1960s. Analysis from Table 2 shows that drought periods in the ESAC were mainly at the interannual scale, reflecting the frequent occurrence of meteorological drought periods in the study area. In addition, similar to the results obtained by Wang *et al.* (2018a), Figure 13 confirms the suitability of ESMD for depicting the interannual evolution trend and drought cycle in the study area. However, the interdecadal variation of the SPEI reconstructed by the ESMD component and the trend R is not ideal for simulating the SPEI change trend. This limitation may be attributed to the filtering of interannual oscillation during the reconstruction of SPEI interdecadal variation (Zhao and Xu, 2014).

The characteristics of interannual, seasonal and monthly meteorological droughts in the study area were analyzed using SPEI data spanning 60 years. This comprehensive approach helped to address the shortcomings of previous single-scale studies. Such research can greatly enhance the understanding of the temporal and spatial evolution, trend decomposition characteristics and periodicity of meteorological drought in the ESAC.

4.2 Research limitations

This study analyzed the trend decomposition and drought periods in the study area, providing valuable insights for water resource management and agricultural activities in the ESAC. However, several problems remain unaddressed. First, the SPEI's reliance solely on precipitation and evapotranspiration makes it extremely sensitive to temperature variations, potentially leading to biases in drought detection, such as overestimating drought intensity and duration. Therefore, further studies on the application and comparison of various drought indices should be conducted to develop a more effective meteorological drought index. Second, local water budgets are mainly affected by surface evapotranspiration and precipitation, calculated through various methods that provide different results. Therefore, future studies should explore both the advantages and disadvantages of various evapotranspiration calculation methods (e.g. Hargreaves, Thornthwaite and Penman-Monteith) and their applicability. Third, although the present study focused on the temporal and spatial evolution and periodicity of droughts, it did not consider their driving mechanisms and ecological impacts. Future research should include sensitivity analyses of drought indices with regard to climate change. Finally, although this study calculated the SPEI using meteorological data provided by China's high-density observatory network, specialization from point to grid may introduce deviations and uncertainties. To address this, future studies could use satellite remote sensing data with high spatiotemporal resolution for pixel-scale monitoring and simulation of meteorological drought evolution.

4.3 Practical and social implications

Under the background of ongoing global warming, the climate in China's arid and semi-arid areas has shown a trend toward warming and increased precipitation, signifying an improvement in the local plant environment. In the future, afforestation initiatives and the conversion of farmland to forest and grassland in this region can increase the planting proportion of water-loving tree species to maximize ecological benefits. In addition, this study revealed that in relatively water-scarce regions of China, drought duration was primarily influenced by interannual oscillations (3.1 and 7.3 years). This suggests that governments and nongovernmental organizations in the region should pay attention to the short-term drought periods in the ESAC, particularly when implementing ecological restoration and conservation projects such as establishing forest reserves and enhancing high-quality farmland.

5. Conclusion

This study focused on the evolution of drought patterns and the complexities of periodicity in the ESAC. Using the PM formula, nonparametric trend analysis, BG segmentation and ESMD method, the trend decomposition and periodic characteristics of drought were revealed. The main conclusions are as follows.

The temporal scale of SPEI exhibited a negative correlation with its sensitivity to single- or short-term weather fluctuations. Although the SPEI increased significantly in both China and the study area, the overall drought station ratio decreased. In the study area, the annual,

seasonal and monthly SPEI increase rates, as well as the number and severity of drought years, surpassed those in China. The interannual variation in the drought station ratio in both regions exhibited phase variations. Specifically, the drought station ratio showed a significant decline from the 1960s to the 1990s, followed by an upward trend since the 1990s. Seasonally, the drought station ratio decreased overall in China and the study area with a significantly higher rate of decrease observed in the study area compared to China.

The spatial instability of moderate or severe drought frequency and intensity in different seasons generally weakened from 1966 to 1983 and 1984 to 2018 compared to the period from 1961 to 1965. The ESMD method demonstrated good applicability in capturing the evolution trend and periodicity of SPEI in the study area. The cumulative variance contribution rate of the main period of interannual variation of the decomposed SPEI-12 was 70.22%, with interannual oscillation playing a dominant role in SPEI-12 variation.

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