SPEI-based Analysis of Spatiotemporal Variation Characteristics of Drought in the Wei River Basin Postprint

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Abstract

Using the Standardized Precipitation Evapotranspiration Index (SPEI) as the evaluation metric, and based on measured precipitation and temperature data from 28 meteorological stations in the Wei River Basin from 1961 to 2017, this study employs methods including the Mann-Kendall (M-K) trend test, Empirical Orthogonal Function (EOF) decomposition, and wavelet transform to analyze the spatiotemporal variation characteristics of drought in the Wei River Basin, and investigates the correlation between drought in the Wei River Basin and six large-scale climate factors, further exploring the potential influence of major climate factors on the spatiotemporal distribution characteristics of drought in the basin. The results indicate that the Wei River Basin exhibited an overall drying trend during 1961-2017. Through EOF decomposition, the drought distribution field in the Wei River Basin primarily exhibits three typical modal patterns: a global pattern, a northwest-southeast opposite distribution pattern, and an east-west opposite distribution pattern. Meanwhile, the large-scale climate factor Southern Oscillation Index (SOI) demonstrates a better correlation with the basin' s drought distribution field and exerts a strong influence on drought variation in this region.

Full Text

Temporal-Spatial Variation Characteristics of Drought in the Weihe River Basin Based on SPEI

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Abstract

The Weihe River Basin is located in the semiarid and semihumid transition region of northern China and experiences frequent drought events; therefore, study of droughts in the Weihe River Basin is of great importance. Based on the precipitation and temperature data from 28 meteorological stations, the spatial and temporal variation characteristics of dryness were analyzed by using the Mann-Kendall (M-K) trend test, empirical orthogonal functions, and wavelet transform analysis. At the same time, the relationship between drought characteristics and six large-scale climatic factors was studied, and the potential impact of the main factors on the spatial and temporal characteristics of drought was further discussed. According to the research, we obtained results showing that the Weihe River Basin exhibits a drought trend between 1961 and 2017. Particularly, after 1990, the drought degree and number of drought phenomena in the basin increased greatly and the average Standardized Precipitation Evapotranspiration Index (SPEI) decreased from 0.34 during 1961–1990 to -0.37 during 1991–2017. Empirical orthogonal function analysis shows that there are three typical modes in the wet and dry distribution field of the Weihe River Basin. The global type with corresponding modal eigenvalues of 50.43% is characterized by either drought or humidity and is the main control mode of dry distributions in the Weihe River Basin; northwest-southeast reverse distribution type with corresponding modal eigenvalues of 17.35% shows that the northwest and southeast regions have different drought characteristics; east-west reverse distribution type with corresponding modal eigenvalues of 5.06% shows that the eastern and western regions have different drought characteristics. Finally, the research reveals that the Southern Oscillation Index (SOI), which represents ENSO events, exhibits the strongest correlation with drought distribution in the Weihe River Basin and from the perspective of phase analysis, abnormal SOI variations will generally bring more drought events to the Weihe River Basin.

Keywords: Weihe River Basin; drought; standardized precipitation evapotranspiration index; empirical orthogonal function; wavelet transform analysis

1. Introduction

Drought is a complex natural hazard that significantly impacts agriculture, water resources, and ecosystems. The Weihe River Basin, situated in the critical semiarid to semihumid transition zone of northern China, is particularly vulnerable to drought events. Understanding the spatiotemporal patterns of drought in this region is essential for water resource management and disaster mitigation. This study employs the Standardized Precipitation Evapotranspiration Index (SPEI) to analyze drought characteristics from 1961 to 2017, integrating multiple statistical methods to elucidate the underlying patterns and climatic drivers.

2. Data and Methods

2.1 Data Collection The analysis utilized monthly precipitation and temperature data from 28 meteorological stations distributed across the Weihe River Basin covering the period 1961–2017. Six large-scale climate indices were selected for teleconnection analysis: the Southern Oscillation Index (SOI), Pacific Decadal Oscillation (PDO), North Pacific Index (NP), North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and Atlantic Multidecadal Oscillation (AMO).

2.2 Mann-Kendall Trend Test The Mann-Kendall (M-K) test is a non-parametric statistical method widely used for detecting monotonic trends in time series data [**?**]. To address potential serial autocorrelation, the trend-free pre-whitening (TFPW) procedure was applied prior to conducting the M-K test [**?**, **?**]. The test statistic is computed as follows:

Given a time series $\{x_i, i = 1, 2, \ldots, n\}$, the M-K test evaluates the null hypothesis of no trend. The TFPW method first removes the trend component, then pre-whitens the series to eliminate autocorrelation effects before applying the standard M-K test.

2.3 Empirical Orthogonal Function Analysis Empirical Orthogonal Function (EOF) analysis, also known as Principal Component Analysis (PCA), was employed to decompose the spatiemporal variability of SPEI into distinct spatial modes and their associated temporal components [**?**, **?**]. The method reduces the dimensionality of the dataset while preserving the dominant patterns of variability.

The EOF decomposition follows these steps:

(1) Construct the data matrix $\mathbf{X}_{m\times n}$, where m represents the number of spatial points (stations) and n represents the number of temporal observations.

(2) Compute the covariance matrix $\mathbf{C}_{m\times m} = \mathbf{X}\mathbf{X}^T$.

(3) Solve the eigenvalue problem: $\mathbf{C}_{m\times m} \times \mathbf{V}_{m\times m} = \mathbf{V}_{m\times m} \times \mathbf{E}_{m\times m}$, where $\mathbf{V}_{m\times m}$ contains the eigenvectors (spatial modes) and $\mathbf{E}_{m\times m}$ is a diagonal matrix of eigenvalues $\lambda_1, \lambda_2, \ldots, \lambda_m$.

(4) The principal components (PCs) are obtained by projecting the original data onto the eigenvectors: $\mathbf{PC}_{m\times n} = \mathbf{V}^T_{m\times m} \times \mathbf{X}_{m\times n}$.

The variance contribution of each mode is calculated as:

$$\text{Contribution} = \frac{\lambda_k}{\sum_{i=1}^{m} \lambda_i} \times 100\%$$

Significant modes were identified using the North rule of thumb [**?**], with eigenvalues exceeding the 95% confidence level threshold:

$$\Delta\lambda_k = \lambda_k \sqrt{\frac{2}{N^*}}$$

where N^* represents the effective number of independent samples.

2.4 Wavelet Transform Analysis

2.4.1 Continuous Wavelet Transform Continuous Wavelet Transform (CWT) was applied to examine the multi-scale temporal characteristics of SPEI and climate indices [**?**, **?**]. The Morlet wavelet function was selected due to its optimal time-frequency localization properties:

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

where t is time and ω_0 is the non-dimensional frequency (taken as $\omega_0 = 6$).

The wavelet coefficients are computed as:

$$W_n(s) = \sum_{i=0}^{N-1} x_i \left[\psi^* \left(\frac{(i-n)\delta t}{s} \right) \right]$$

where s is the wavelet scale, δt is the time step, and the asterisk denotes the complex conjugate.

2.4.2 Cross-Wavelet Analysis Cross-wavelet transform was used to investigate the phase relationship between SPEI and climate indices, particularly SOI. This method identifies regions in time-frequency space where two series exhibit high common power and consistent phase relationships.

3. Results

3.1 Drought Trend Analysis The M-K test revealed a significant drying trend in the Weihe River Basin during 1961-2017. The trend intensified markedly after 1990, with the average SPEI declining from 0.34 in the period 1961-1990 to -0.37 in 1991-2017. This shift indicates a transition from predominantly wet to predominantly dry conditions.

Table 1. Drought classification standard of SPEI

SPEI Range	Drought Category
SPEI > -0.5	Normal
-1.0 < SPEI -0.5	Mild drought
-1.5 < SPEI -1.0	Moderate drought
-2.0 < SPEI -1.5	Severe drought
SPEI -2.0	Extreme drought

3.2 Spatial Patterns of Drought EOF analysis identified three dominant modes of drought variability:

1. **Global Mode (50.43% variance)**: Characterized by uniform drought or humidity across the entire basin, representing the primary control on dry-wet distributions.
2. **Northwest-Southeast Reverse Mode (17.35% variance)**: Exhibits opposite drought conditions between the northwestern and southeastern regions, reflecting the influence of topographic gradients and moisture transport pathways.
3. **East-West Reverse Mode (5.06% variance)**: Shows contrasting drought characteristics between eastern and western sub-regions, likely associated with different responses to large-scale circulation patterns.

Table 3. Correlation coefficients between climate indices and SPEI, PCs

Index	SPEI	PC1	PC2	PC3
SOI	0.49	0.41	0.37	-0.28
PDO	-0.17	0.16	0.05	-0.07
NP	0.11	-0.12	0.05	-0.09
NAO	-0.16	0.16	0.06	0.16
AO	0.05	-0.06	0.17	0.09
AMO	-0.24	-0.24	-0.03	-0.05

3.3 Teleconnection with Climate Indices Among the six climate indices analyzed, SOI demonstrated the strongest correlation with SPEI ($r = 0.49$) and the first principal component ($r = 0.41$), indicating that ENSO dynamics are the primary large-scale driver of drought variability in the Weihe River Basin.

Cross-wavelet analysis between SOI and SPEI revealed significant coherence at multiple time scales:

- **PC1 and SOI**: Strong correlation at 9-13 year periods, particularly during 1995-2010, with SOI leading SPEI variations.
- **PC2 and SOI**: Significant coherence at 4-7 year periods during 1980-1995, reflecting the typical ENSO cycle.

- **PC3 and SOI**: Coherence at 8–14 year periods during 1985–2015, suggesting decadal-scale interactions.

[Figure 1: see original paper]

Figure 1. Topographic map of the Weihe River Basin and meteorological stations

[Figure 7: see original paper]

Figure 7. Cross-wavelet transform between SOI and SPEI, PCs

4. Discussion

The pronounced drying trend after 1990 aligns with observed warming and altered atmospheric circulation patterns over northern China. The EOF results highlight that while the basin tends to experience drought uniformly (global mode), significant regional differences exist, particularly between the northwestern highlands and southeastern lowlands. The strong SOI-SPEI relationship confirms that ENSO variability modulates precipitation and temperature regimes, with El Niño phases generally associated with increased drought frequency. The multi-scale coherence identified through wavelet analysis suggests that ENSO influences operate across interannual to decadal periods, with varying impacts on different sub-regions of the basin.

5. Conclusion

This study demonstrates that the Weihe River Basin has experienced a significant drying trend from 1961 to 2017, with accelerated drought conditions after 1990. EOF analysis reveals three distinct spatial modes controlling drought distribution, with the global uniform mode being dominant. The Southern Oscillation Index emerges as the primary climate driver, showing the strongest correlation with basin-wide drought patterns. These findings enhance understanding of drought mechanisms and provide a scientific basis for drought prediction and water resource management in the region.

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Note: Figure translations are in progress. See original paper for figures.