Spatiotemporal Evolution Patterns of Extreme Precipitation in the Wei River Basin and Its Response to Atmospheric Circulation Factors: Postprint

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Abstract

Based on daily precipitation data from 28 meteorological stations within and around the Wei River basin from 1961 to 2017, six extreme precipitation indices including PRCPTOT, SDII, Rx1day, Rx5day, R95P, and R99P were selected. The spatiotemporal evolution patterns of extreme precipitation in the Wei River basin were comprehensively analyzed using the Mann-Kendall trend test and wavelet transform methods, and the correlation between extreme precipitation indices and six atmospheric circulation anomaly factors was further investigated. The results show that: (1) During 1961–2017, extreme precipitation indices in the Wei River basin showed an overall decreasing trend. Extreme precipitation indices gradually increased from northwest to southeast across the basin, with the southeastern region being wetter than the northwestern region; (2) After 1990, the interannual variability of extreme precipitation indices increased significantly, and the probability of extreme precipitation events in the basin showed an upward trend; (3) Among the selected atmospheric circulation anomaly factors, extreme precipitation in the Wei River basin was most influenced by the Southern Oscillation Index (SOI). The larger the SOI, the greater the probability of low-rainfall conditions in the basin; conversely, the smaller the SOI, the greater the probability of high-rainfall and flood conditions. The results of this study are of great significance for understanding the impact mechanism of climate change on extreme rainfall and for enhancing the capacity to prevent climate-related disasters.

Full Text

Spatial-temporal variations of extreme precipitation indices and their response to atmospheric circulation factors in the Weihe River Basin

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Abstract

Based on daily precipitation data from 28 meteorological stations in and around the Weihe River Basin from 1961 to 2017, six extreme precipitation indices were selected to analyze the spatiotemporal evolution of extreme precipitation using the Mann-Kendall trend test and wavelet transform methods. The study further investigated correlations between extreme precipitation indices and five atmospheric circulation anomaly factors. The results show that: (1) From 1961 to 2017, extreme precipitation indices in the Weihe River Basin showed an overall decreasing trend. The indices gradually increased from northwest to southeast, with the southeastern region being wetter than the northwestern region. (2) After 1990, the interannual variability of extreme precipitation indices increased significantly, indicating a rising probability of extreme precipitation events. (3) Among the selected atmospheric circulation anomaly factors, the Southern Oscillation Index (SOI) had the greatest influence on extreme precipitation in the Weihe River Basin. Higher SOI values correspond to greater probability of low-rainfall conditions, while lower SOI values correspond to greater probability of heavy rainfall and flood events. These findings are significant for understanding the mechanisms of climate change impacts on extreme rainfall and for enhancing climate disaster prevention capabilities.

Keywords: Weihe River Basin; extreme precipitation index; spatiotemporal evolution; atmospheric circulation anomaly factors

1 Introduction

Precipitation constitutes a vital component of the hydrological cycle, with natural flood and drought events being closely related to precipitation patterns. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicates that global temperatures have shown a significant warming trend, particularly in the Northern Hemisphere, where recent warming may be unprecedented in the past 1400 years. Numerous studies have utilized CMIP5 model outputs to evaluate dry and wet region changes across China, demonstrating that the climate-sensitive semi-humid and semi-arid zones are expanding. Under the influence of global climate change, the spatiotemporal patterns of precipitation have undergone significant alterations, leading to changes in water vapor cycling and increased frequency of extreme precipitation events, which severely impact human livelihoods, social stability, and economic development. Therefore, investigating the spatiotemporal evolution of extreme precipitation and its influencing factors under changing environmental conditions is crucial for climate disaster monitoring and flood control planning.

In recent years, increasing attention has been paid to analyzing the spatiotemporal variations and statistical characteristics of extreme precipitation. For instance, Shi Guangxun et al. analyzed extreme precipitation processes in the Yangtze River Basin using data from 756 meteorological stations, employing the Mann-Kendall test and principal component analysis. Wang Chengbo et al. examined multi-scale extreme precipitation characteristics in the Hanjiang River Basin using daily precipitation data combined with peak-over-threshold sampling methods. Ma Mengyang et al. analyzed spatiotemporal variations of extreme precipitation in the Haihe River Basin using linear regression, Mann-Kendall trend tests, and Pearson correlation analysis. Yang Peiyu et al. investigated extreme precipitation in the Yellow River Basin using threshold-based sampling, Kendall correlation analysis, and other methods. While these studies have advanced understanding of extreme precipitation patterns, research specifically focusing on the Weihe River Basin remains limited.

The Weihe River Basin, located in the transitional zone between semi-humid and semi-arid regions of northern China, exhibits distinct seasonal variations. Since the beginning of the 21st century, the basin has experienced frequent flood and drought events. For example, from August to October 2003, the basin encountered three heavy rainfall processes lasting over 60 days, with prolonged duration and high intensity. In September 2011, widespread continuous rainfall caused major floods in both the main stream and tributaries of the Weihe River. Conversely, 1997 and 2001 witnessed prolonged droughts causing severe losses. Feng Xing et al. analyzed precipitation trends and periodic characteristics in the Weihe River Basin using daily precipitation data from 1960-2015, while Zhou Qi et al. examined extreme precipitation events from 1961-2016. However, existing studies have primarily focused on temporal trends, with limited investigation of influencing factors. This study addresses this gap by comprehensively analyzing spatiotemporal evolution patterns of extreme precipitation and their relationships with atmospheric circulation anomaly factors.

2 Materials and Methods

2.1 Study Area

The Weihe River, a first-order tributary of the Yellow River, originates in Weiyuan County, Gansu Province, and flows eastward through Gansu and Shaanxi provinces before joining the Yellow River at Tongguan County. The basin covers approximately 1.35×10^{5} km^2, with elevations ranging from 322 to 3919 m. The western region comprises the Loess Plateau gully area, while the eastern downstream region consists primarily of the Guanzhong Plain. Located in a transitional climate zone, the basin is influenced by the Western Pacific Subtropical High, characterized by hot, rainy summers with occasional droughts, cool and humid autumns, and dry, cold winters controlled by the Mongolian High. Precipitation decreases from southeast to northwest, with the southern Qinling mountainous area receiving abundant precipitation (maximum annual precipitation >1000 mm), while the plain areas receive approximately 500 mm annually.

2.2 Data Sources and Preprocessing

Daily precipitation data from 1961 to 2017 were obtained from 28 uniformly distributed meteorological stations in and around the Weihe River Basin from the China Meteorological Data Sharing Service Network. Data quality control and gap-filling were performed prior to analysis. Figure 1 shows the distribution of meteorological stations and annual average precipitation across the basin.

To investigate relationships between extreme precipitation and atmospheric circulation, five representative anomaly factors were selected: Southern Oscillation Index (SOI), Pacific Decadal Oscillation (PDO), Pacific-North American Teleconnection Index (PNA), North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and Atlantic Multidecadal Oscillation (AMO). These data were sourced from the Earth System Research Laboratory of the National Oceanic and Atmospheric Administration (NOAA) (http://www.esrl.noaa.gov/psd/data/climateindices/list/).

2.3 Extreme Precipitation Indices

Following the recommendations of the World Meteorological Organization (WMO) and the Climate Variability and Predictability (CLIVAR) program, six representative extreme precipitation indices were selected (Table 2): PRCPTOT (total precipitation), SDII (simple daily intensity index), Rx1day (maximum 1-day precipitation), Rx5day (maximum 5-day precipitation), R95P (very wet day precipitation), and R99P (extremely wet day precipitation).

2.4 Mann-Kendall Trend Test

The Mann-Kendall test, widely used in hydro-meteorological statistics, was employed for trend analysis. Prior to testing, the trend-free pre-whitening method was applied to remove autocorrelation from the time series. For a given time series {x , i = 1, 2, …, n}, the autocorrelation coefficient r_1 was calculated, followed by the regression coefficient γ. The autocorrelation was then removed using x = x - $\gamma \cdot$ x $_1$. The Mann-Kendall statistic UF was computed based on the rank sequence, where UF > 0 indicates an increasing trend and UF < 0 indicates a decreasing trend. For significance level $\alpha = 0.05$, |UF | > 1.96 indicates a statistically significant trend.

2.5 Wavelet Analysis

2.5.1 Continuous Wavelet Transform Continuous Wavelet Transform (CWT) provides an adaptive time-frequency window that adjusts according to frequency—larger frequency windows at high frequencies and larger time windows at low frequencies. This enables extraction of multi-scale temporal structures and local characteristics. The Morlet wavelet, commonly used in hydro-meteorological research, was adopted with the form (t) = $\pi^{-1\ 4}e^{(i\omega_0 t)e}$(-$t^2/2$), where $\omega_0 = 6$. For a discrete time series X , the wavelet transform is defined as W (s) = Σ $_0$ $^{-1}$ X *[(n -n)δt/s], where δt is the time step, s is the scale factor, and* denotes the complex conjugate.

2.5.2 Cross-Wavelet Transform Cross-wavelet transform combines wavelet analysis with cross-spectrum analysis to reveal energy resonance and covariance distributions between two time series in the time-frequency domain. For time series X and Y with wavelet transforms W and W , the cross-wavelet transform is W = W W *, where* denotes the complex conjugate. The absolute value |W | represents the cross-wavelet power spectrum, which was used to analyze the response characteristics of extreme precipitation indices to atmospheric circulation anomalies.

3 Results

3.1 Spatiotemporal Variation Characteristics

3.1.1 Temporal Variation Based on daily precipitation data from 28 stations, extreme precipitation indices were calculated and area-averaged using Thiessen polygons. PRCPTOT showed a significant decreasing trend from 1961 to 2017, with a multi-year average of 544.6 mm, decreasing from 567.9 mm to 518.8 mm (a reduction of 8.65%). This aligns with Feng Xing et al.'s finding of decreasing annual precipitation concentrated in the early 1990s. SDII showed an increasing trend, with a multi-year average of 8.4 mm, indicating intensifying precipitation. Rx1day exhibited a significant increasing trend, with an average of 51 mm, ranging between 39.6–63.4 mm. Rx5day showed no significant overall trend, with a multi-year average of 84.7 mm, though interannual variability increased after 1990. R95P and R99P, representing precipitation sums above the 95th and 99th percentiles, showed increasing trends with averages of 134 mm and 22–81 mm, respectively.

3.1.2 Spatial Distribution Extreme precipitation indices displayed similar spatial patterns, gradually increasing from northwest to southeast (Figure 3). PRCPTOT ranged from 345–741 mm, SDII from 7.0–9.7 mm, Rx1day from 39.6–63.4 mm, and Rx5day from 62–111 mm. Overall, the southeastern basin was wetter than the northwestern region. Trend analysis revealed that most stations showed decreasing trends for PRCPTOT, while Rx1day and Rx5day increased at stations primarily located in the northern and middle reaches.

3.2 Periodic Characteristics

Continuous wavelet transform analysis revealed periodic features of extreme precipitation indices (Figure 4). PRCPTOT showed significant periods of 2–4 years and 6–10 years. Rx1day exhibited 2–5 year and 8–13 year cycles. Rx5day displayed 1–3 year and 6–10 year periods. R95P and R99P showed 2–6 year and 8–16 year cycles. The red regions in the power spectrum indicate stronger periodic signals, with black contours denoting significance at the 95% confidence level.

3.3 Response to Atmospheric Circulation Anomalies

Correlation analysis between extreme precipitation indices and atmospheric circulation factors showed that SOI had the strongest influence (Table 4). All correlation coefficients between SOI and extreme precipitation indices passed significance tests at the 0.05 level, with SOI-PRCPTOT correlations being the largest. Cross-wavelet analysis between extreme precipitation indices and SOI revealed consistent patterns (Figure 5). The response was concentrated in the 8–13 year band, showing negative correlations. Arrows in the power spectrum indicate phase relationships: rightward arrows show in-phase relationships, while leftward arrows show anti-phase relationships. The analysis indicates that higher SOI values correlate with lower precipitation (drought probability), while lower SOI values correlate with higher precipitation (flood probability). This negative correlation is consistent with studies linking ENSO events to precipitation anomalies in northwestern China, where El Niño events (negative SOI phase) enhance precipitation in northern regions through strengthened Hadley circulation and intensified Western Pacific Subtropical High.

4 Conclusions

Based on daily precipitation data from 28 meteorological stations in the Weihe River Basin (1961–2017), this study analyzed spatiotemporal variations of six extreme precipitation indices (PRCPTOT, SDII, Rx1day, Rx5day, R95P, R99P) using Mann-Kendall trend tests and wavelet transform methods, and investigated correlations with five atmospheric circulation anomaly factors. The main conclusions are:

1. From 1961 to 2017, extreme precipitation indices in the Weihe River Basin showed decreasing trends. After 1990, interannual variability increased

significantly, with rising probability of extreme precipitation events.

2. Spatially, extreme precipitation indices increased from northwest to southeast, with the southeastern region being wetter than the northwestern region. Most stations exhibited decreasing trends, except for some local areas.
3. Among atmospheric circulation anomaly factors, SOI had the most significant impact on extreme precipitation in the Weihe River Basin. Cross-wavelet analysis revealed a dominant periodicity of approximately 8–13 years, with negative phase relationships. Higher SOI values increase the probability of low-rainfall conditions, while lower SOI values increase the probability of heavy rainfall and flood events.

These findings enhance understanding of climate change impacts on extreme precipitation and improve capacity for climate disaster prevention in the Weihe River Basin.

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