Spatiotemporal Evolution Patterns of Extreme Precipitation in Northern Shanxi and Its Response to Atmospheric Circulation Factors: Postprint

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Abstract

Based on daily precipitation data from 28 national meteorological stations in northern Shanxi for the period 1972–2020, this study employed eight extreme precipitation indices and utilized methods including linear regression, Pearson correlation analysis, continuous wavelet transform, and cross-wavelet transform analysis to investigate the spatiotemporal variations of extreme precipitation in northern Shanxi and their correlations and periodic characteristics with atmospheric circulation factors. The results indicate: (1) Temporally, all eight extreme precipitation indices in northern Shanxi increased during the late 1970s and from the late 2000s to the 2010s. Specifically, annual total precipitation (PRCPTOT), number of days with precipitation \$ \$10 mm (R10mm), very wet day precipitation (R95P), extremely wet day precipitation (R99P), maximum 1 d precipitation (Rx1day), and maximum 5 d precipitation (Rx5day) all increased; daily precipitation intensity (SDII) was significantly enhanced, and consecutive wet days (CWD) also increased slightly. Precipitation was abnormally low throughout the 1980s. (2) Spatially, the extreme precipitation indices exhibited a gradual increasing trend from northeast to southwest. Analysis of station-level trends revealed that most stations showed increasing trends in extreme precipitation indices, with the most significant increases observed at stations in southwestern Xinzhou City. Stations in Shuozhou City and southeastern Xinzhou City exhibited increasing trends in both PRCPTOT and SDII, but a decreasing trend in CWD, suggesting a higher probability of extreme precipitation events in these regions. (3) Wavelet transform analysis revealed that extreme precipitation indices in northern Shanxi exhibited periodic characteristics of approximately 4 a from 1990 to 2020. Among the selected atmospheric circulation indices, the North Atlantic Oscillation index (NAO) had the most significant influence on extreme precipitation in northern Shanxi. Higher

NAO values corresponded to lower PRCPTOT, R10mm, R95p, R99p, Rx1day, Rx5day, and SDII, as well as fewer CWD, indicating a greater likelihood of drought conditions in northern Shanxi. Conversely, lower NAO values tended to result in heavy rainfall and flooding. The research findings can provide a scientific theoretical basis for the prevention and mitigation of meteorological disasters in northern Shanxi.

Full Text

Preamble

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Temporal and Spatial Evolution of Extreme Precipitation and Its Response to Atmospheric Circulation Factors in Northern Shanxi Province

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Abstract

Based on daily precipitation data from 28 national meteorological stations in northern Shanxi Province from 1972 to 2020, this study investigated the spatiotemporal evolution of extreme precipitation and its correlation with atmospheric circulation factors using linear regression, Pearson correlation analysis, continuous wavelet transform, and cross-wavelet transform. Eight extreme precipitation indices were selected from the core indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) of the World Meteorological Organization. The results reveal three key findings. First, temporally, all eight extreme precipitation indices increased significantly during the late 1970s and from the late 1990s to early 2000s. Specifically, annual total precipitation (PRCPTOT), number of days with precipitation above 10 mm (R10mm), strong precipitation (R95P), extremely strong precipitation (R99P), maximum 1-day precipitation (Rx1day), and maximum 5-day precipitation (Rx5day) all showed upward trends. The simple daily intensity index

(SDII) strengthened markedly, while consecutive wet days (CWD) increased slightly. In contrast, the 1980s experienced unusually low precipitation throughout the decade. Second, spatially, the extreme precipitation indices exhibited a gradual increase from northeast to southwest. Analysis of station-level trends indicates that most stations showed upward trends, with the most significant increases occurring in the southwestern part of Xinzhou City. While PRCPTOT and SDII in Shuozhou City and southeastern Xinzhou City displayed increasing trends, CWD showed a decreasing trend, suggesting a higher probability of extreme precipitation events in these regions. Third, wavelet analysis identified a prominent periodicity of approximately 4 years in the extreme precipitation indices over the past 30 years. Among the selected atmospheric circulation indices, the North Atlantic Oscillation (NAO) exerted the most pronounced influence on extreme precipitation in northern Shanxi. When the NAO index is larger, PRCPTOT, R10mm, R95P, R99P, Rx1day, Rx5day, and SDII all decrease correspondingly, while CWD also declines, indicating a greater likelihood of drought conditions. Conversely, smaller NAO values are associated with increased precipitation and higher flood risk. These findings provide a scientific basis for predicting extreme precipitation events and formulating disaster prevention strategies in northern Shanxi.

Keywords: extreme precipitation indices; spatiotemporal distribution; atmospheric circulation anomaly factor; wavelet analysis; northern Shanxi

Introduction

The IPCC Sixth Assessment Report indicates that since the 1950s, the global mean precipitation rate over land has accelerated, with both the frequency and intensity of extreme precipitation showing increasing trends. Heatwaves, droughts, and extreme heavy precipitation events have continued to intensify significantly, with a tendency toward more severe conditions in the future. Numerous scholars have conducted in-depth research on the circulation factors influencing extreme precipitation, revealing that El Niño-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), tropical Pacific sea surface temperatures, the East Asian summer monsoon, the Indian Ocean Dipole, and the Western Pacific subtropical high are all closely related to the occurrence of extreme precipitation events.

Recent studies have confirmed significant increases in precipitation days and extreme precipitation across global regions. In North America, extreme precipitation amounts show an upward trend, while in South America, the frequency of extreme precipitation has strengthened significantly. Across most of Asia, extreme precipitation events have become more frequent and intense. Research in China has demonstrated that the NAO exhibits significant periodic oscillations at interdecadal timescales and correlates well with extreme precipitation responses in the middle and lower reaches of the Yangtze River. Other studies have identified significant resonance periods between atmospheric oscillations and extreme precipitation in the Yangtze River Basin, with notable differences across various time-frequency domains, indicating that external forcing factors can influence extreme precipitation variability, with large-scale climate factors serving as important drivers.

In recent years, increasing attention has been devoted to the periodic characteristics of extreme precipitation. Researchers have employed continuous wavelet transform and cross-wavelet methods to investigate the periodic characteristics of extreme precipitation indices and their responses to atmospheric circulation factors in river basins such as the Weihe and Guanzhong Plain. While some studies have examined extreme precipitation indices across Shanxi Province, research on the underlying mechanisms affecting extreme precipitation specifically in northern Shanxi remains limited.

Shanxi Province has historically been characterized by frequent drought conditions, with the situation worsening after the 1980s alongside accelerated global warming, significantly impacting agricultural production. Northern Shanxi receives even less natural precipitation, making crop yields highly dependent on weather and climate conditions. Therefore, a deeper investigation into the relationship between extreme precipitation indices and atmospheric circulation indices in this region is essential. This study provides a comprehensive analysis of the spatiotemporal variability, periodic oscillation characteristics, and responses to atmospheric circulation factors of extreme precipitation indices in northern Shanxi, offering theoretical support for extreme precipitation forecasting, agricultural meteorological services, and government-led drought and flood disaster prevention efforts.

1.1 Study Area

Northern Shanxi Province ($111.08°–114.26°E, 38.39°–40.37°N$) comprises the cities of Datong, Shuozhou, and Xinzhou from north to south, covering an area of approximately [value] km^2. The region features complex and varied terrain, bounded by Heng Mountain in the south and Hongtao Mountain in the north, adjacent to the Taihang Mountains to the east and the Lüliang Mountains to the west. The area includes the Datong Basin and Xinzhou Basin between mountain ranges, and is characterized by a temperate cold semi-arid climate with elevations ranging from 759.4 to 2208.3 m.

1.2 Data Sources

Daily precipitation data from 1972 to 2020 were obtained from 28 national meteorological stations in northern Shanxi Province [Figure 1: see original paper]. Extreme precipitation indices were calculated and quality-controlled using the RClimDex1.0 software. Atmospheric circulation indices, including the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), West Pacific Pattern (WP), North Pacific Pattern (NP), Southern Oscillation

Index (SOI), Atlantic Multidecadal Oscillation (AMO), sunspot numbers, Pacific Decadal Oscillation (PDO), and Asian polar vortex area index, were sourced from the National Climate Center's Climate Monitoring Division (http://cmdp.ncc-cma.net/cn/monitoring.htm).

1.3 Research Methods

Based on the climatic characteristics of northern Shanxi, eight core extreme precipitation indices recommended by the ETCCDI were selected: annual total precipitation (PRCPTOT), number of days with precipitation $ $10 mm (R10mm), strong precipitation (R95P), extremely strong precipitation (R99P), maximum 1-day precipitation (Rx1day), maximum 5-day precipitation (Rx5day), simple daily intensity index (SDII), and consecutive wet days (CWD). Linear regression was employed to analyze climate change trends, inverse distance weighting interpolation in ArcGIS was used to generate spatial distribution maps, and Pearson correlation analysis, continuous wavelet transform, and cross-wavelet transform were applied to examine correlations and periodic characteristics between extreme precipitation indices and atmospheric circulation factors.

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2 Results and Analysis

2.1 Spatiotemporal Evolution Characteristics of Extreme Precipitation Indices in Northern Shanxi

2.1.1 Temporal Variation Characteristics Figure 2 illustrates the temporal trends of extreme precipitation indices in northern Shanxi from 1972 to 2020. PRCPTOT increased at a rate of $8.022\ \text{mm}\cdot(10\text{a})^{-1}$, R10mm at $0.425\ \text{d}\cdot(10\text{a})^{-1}$, R95P at $0.204\ \text{mm}\cdot(10\text{a})^{-1}$, R99P at $4.18\ \text{mm}\cdot(10\text{a})^{-1}$, Rx1day at $1.443\ \text{mm}\cdot(10\text{a})^{-1}$, Rx5day at $0.744\ \text{mm}\cdot(10\text{a})^{-1}$, and SDII at $1.321\ \text{mm}\cdot(10\text{a})^{-1}$. CWD decreased at a rate of $0.026\ \text{d}\cdot(10\text{a})^{-1}$. Only R99P and SDII passed the significance test at the $\alpha = 0.05$ level, indicating a strengthening trend in precipitation intensity, though the upward trends of other indices were not statistically significant.

2.1.2 Spatial Distribution and Trend Characteristics Spatially, all extreme precipitation indices exhibited a pattern of gradual increase from northeast to southwest [Figure 3: see original paper]. Station-level trend analysis reveals that 82.1% of stations showed upward trends in PRCPTOT, with the most significant increases in southwestern Xinzhou City. Stations in Shuozhou City and southeastern Xinzhou City displayed increasing trends in both PRCPTOT and SDII, but decreasing trends in CWD, suggesting a higher probability of extreme precipitation events in these areas. Specifically, 89.3% of stations showed upward trends in R10mm, with 57.1% passing significance tests. For Rx1day, 67.9% of stations exhibited upward trends, with significant increases in Xinzhou District, Wutai Mountain, and Dingxiang County. Rx5day showed upward trends at 75.0% of stations, while SDII increased at 53.6% of stations, with significant rises in Xinzhou District and Dingxiang County. These findings align with previous research indicating that extreme heavy precipitation days in northern Shanxi have increased slightly since the 1970s, with spatial distributions shifting from northeast to southwest.

2.2 Periodic Characteristics of Extreme Precipitation Indices

Continuous wavelet transform reveals the temporal variation characteristics of extreme precipitation indices. As shown in Figure 4, significant periodicities are evident across multiple timescales. PRCPTOT exhibits significant 2–3-year and 4–5-year periodic oscillations, with stronger energy concentrated in 7–8-year cycles. R10mm shows 2–4.5-year periodic oscillations, while Rx1day displays 1–1.5-year and 4–6-year cycles. Rx5day exhibits 2–4-year periodic oscillations, and CWD shows 4.5–8-year cycles. SDII demonstrates 1–2-year and 4–6-year periodic oscillations. Overall, the extreme precipitation indices in northern Shanxi over the past 30 years show a prominent periodic characteristic of approximately 4 years, consistent across multiple indices.

2.3 Response of Extreme Precipitation to Atmospheric Circulation Anomaly Factors

Correlation analysis between extreme precipitation indices and atmospheric circulation factors indicates that NAO exhibits the most significant influence. Rx1day and Rx5day show significant negative correlations with NAO, passing significance tests at $\alpha = 0.05$. Rx1day also demonstrates significant negative correlations with the West Pacific Pattern and significant positive correlations with the North Pacific Pattern and sunspot numbers, with correlation coefficients passing $\alpha = 0.05$ significance tests. The Asian polar vortex area index shows significant negative correlations with Rx1day and Rx5day, and significant positive correlations with R10mm.

Cross-wavelet transform analysis further elucidates the time-frequency relationships and periodic co-variation between extreme precipitation indices and NAO [Figure 5: see original paper]. High-energy regions are concentrated at resonance periods of 1–3 years, 1.5–4.0 years, and 1.5–2.0 years. During these periods, PRCPTOT, R10mm, Rx1day, and Rx5day exhibit negative phase relationships with NAO, indicating that when NAO values are larger, these precipitation indices decrease correspondingly. The phase angles suggest that precipitation indices lag NAO by approximately 3–8 months. These results demonstrate that NAO serves as the primary atmospheric circulation factor influencing extreme precipitation in northern Shanxi, with larger NAO values favoring drought conditions and smaller values promoting flood events.

3 Conclusions

This study investigated the spatiotemporal evolution, periodic characteristics, and atmospheric circulation responses of extreme precipitation indices in northern Shanxi Province from 1972 to 2020. The main conclusions are as follows:

1. **Temporal Evolution:** Extreme precipitation indices in northern Shanxi increased significantly during the late 1970s and from the late 1990s to early 2000s. PRCPTOT, R10mm, R95P, R99P, Rx1day, and Rx5day all showed upward trends, while SDII strengthened markedly and CWD increased slightly. In contrast, the 1980s experienced precipitation anomalies that were consistently below normal.

2. **Spatial Distribution:** All extreme precipitation indices exhibited a clear pattern of increase from northeast to southwest. Most stations showed upward trends, with the most significant increases occurring in southwestern Xinzhou City. While PRCPTOT and SDII increased in Shuozhou City and southeastern Xinzhou City, CWD decreased, indicating a higher probability of extreme precipitation events in these regions.

3. **Periodic Characteristics and Atmospheric Circulation Response:** Wavelet analysis revealed a prominent ~4-year periodicity in extreme precipitation indices over the past 30 years. Among atmospheric circulation factors, NAO exerted the most significant influence, showing negative correlations with multiple precipitation indices. Larger NAO values correspond to reduced precipitation amounts and fewer wet days, increasing the probability of drought in northern Shanxi, whereas smaller NAO values enhance precipitation and flood risk. These findings provide a scientific theoretical basis for improving meteorological disaster prevention and agricultural meteorological services in northern Shanxi.

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