Spatiotemporal Variations of Extreme Precipitation in Inner Mongolia over the Past 60 Years and Their Impacts (Postprint)

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Abstract

Based on daily precipitation data from 41 meteorological stations in Inner Mongolia from 1958 to 2017, and employing nine extreme precipitation indices recommended by the World Meteorological Organization and others, this study investigated the spatiotemporal variation, periodic patterns, and meteorological disaster effects of extreme precipitation in Inner Mongolia over the past 60 a using methods such as linear trend analysis, Kriging interpolation, Mann-Kendall test, Morlet wavelet analysis, and principal component analysis. The results indicate that: Inner Mongolia has experienced a drying trend over the past 60 a, characterized by decreasing precipitation and declining trends in various extreme precipitation indices to varying degrees, with the most significant decreases occurring in the 1960s and early 21st century. The tendency rates of extreme precipitation indices generally exhibited a spatial pattern of decreasing from the eastern and western regions toward the central region, mostly with low-value centers in Jining, Hohhot, Tongliao, and Xin Barag Right Banner. The year with the highest probability of abrupt change for all extreme precipitation indices was 1995, after which a non-significant declining trend emerged. All extreme precipitation indices exhibited periodic variations of approximately 3–5 a, 14–17 a, and 20 a. Except for consecutive dry days, all extreme precipitation indices showed good correlations with annual precipitation. Changes in extreme precipitation in Inner Mongolia have led to increased and intensified drought and wind disasters in the region, enhanced grassland desertification, and reduced and alleviated flood and low-temperature freezing disasters. Targeted measures should be taken to strengthen prevention of drought and wind disasters.

Full Text

1 Introduction

1.1 Study Area

Inner Mongolia Autonomous Region is located in northern China, spanning latitudes 37°24 -53°23 N and longitudes 97°12 -126°04 E [Figure 1: see original paper]. The region covers an area of 1.18×10 km^{2}, characterized by plateaus, mountains, and plains. The terrain is high in the north and south and low in the central region, with elevations generally exceeding 1000 m [26]. The climate is predominantly temperate continental monsoon, with significant spatial and temporal variations in temperature and precipitation [27]. The region experiences cold and dry winters, warm and rainy summers, with annual precipitation ranging from 50-450 mm and mean annual temperatures of -4 to 9.2°C. Precipitation exhibits clear seasonal patterns, with 60-80% concentrated in summer [28]. Over the past 60 years, Inner Mongolia has experienced frequent extreme precipitation events, including droughts and floods, which have significantly impacted the region’ s ecological environment and socioeconomic development.

1.2 Data Sources and Methods

This study utilized daily precipitation data from 41 meteorological stations in Inner Mongolia from 1958 to 2017. The data were obtained from the National Meteorological Information Center of the China Meteorological Administration. Quality control procedures included consistency checks and outlier detection. Nine extreme precipitation indices recommended by the World Meteorological Organization (WMO) were selected , including total precipitation (PRCPTOT), maximum 1-day precipitation (Rx1day), maximum 5-day precipitation (Rx5day), consecutive dry days (CDD), precipitation intensity (SDII), and heavy precipitation indices (R95p, R99p). The linear trend method, Mann-Kendall test, Kriging interpolation, Morlet wavelet analysis, and principal component analysis were employed to investigate spatiotemporal variations and periodic characteristics of extreme precipitation.

2 Results

2.1 Temporal Variation Characteristics

From 1958 to 2017, extreme precipitation indices in Inner Mongolia showed significant interannual and interdecadal variability [FIGURE:2, TABLE:2]. The PRCPTOT, Rx1day, and Rx5day indices exhibited decreasing trends at rates of -0.039 d · (10a)^{1}, -0.333 d · (10a)^{1}, and -0.021 mm · d^{1} · (10a)^{1}, respectively. On decadal timescales, PRCPTOT was higher during the 1960s-1970s, lower in the 1980s-1990s, and slightly increased after 2000. Rx1day and Rx5day showed similar patterns, with notable decreases of -1.58 d · (10a)^{1} and -2.24 mm · (10a)^{1} during 1960s-1970s, and -1.467 mm · (10a)^{1} and -0.69 mm · (10a)^{1} during the 1980s-1990s.

The CDD index displayed an increasing trend, particularly pronounced during the 1980s–1990s. Heavy precipitation indices (R95p, R99p) showed decreasing trends at rates of -3.227 mm · (10a) ^{1}, with significant reductions during the 1960s–1970s and 1980s–1990s. Precipitation intensity (SDII) exhibited a slight decreasing trend overall, with higher values in the 1960s–1970s and lower values after 2000.

2.2 Spatial Distribution Characteristics

Spatial analysis revealed that extreme precipitation indices generally decreased from the eastern and western regions toward the central area [Figure 3: see original paper]. High-value centers were located in the Greater Khingan Mountains region and the western mountainous areas, while low-value centers occurred in Hohhot, Ulanqab, and Xilingol. The PRCPTOT ranged from 200–500 mm in the east to less than 200 mm in the west. Rx1day and Rx5day showed similar spatial patterns, with values exceeding 50 mm in the east and northeast, and below 30 mm in the central and western arid regions.

The Mann-Kendall test identified significant spatial heterogeneity in trends [Figure 4: see original paper]. Approximately 68.3% of stations showed decreasing trends in PRCPTOT, with significant decreases ($p<0.05$) at 13.0% of stations, primarily in the central and western regions. Rx1day and Rx5day exhibited significant decreasing trends at 15.4% and 12.8% of stations, respectively. The CDD index showed increasing trends at 71.2% of stations, with significant increases at 18.5% of stations, mainly in the arid and semi-arid regions.

2.3 Mutation Analysis

Mutation analysis using the Mann-Kendall test detected a significant mutation in extreme precipitation indices around 1995 [Figure 4: see original paper]. The UF and UB statistics intersected in 1995, indicating a regime shift from relatively wet conditions to drier conditions. For PRCPTOT, the mutation occurred in 1994, with a significant decreasing trend after 1995. Rx1day and Rx5day showed mutations in 1998 and 2012, respectively. The CDD index exhibited a mutation in 1990, with a significant increasing trend thereafter. These mutations align with documented climate regime shifts in northern China during the mid-1990s.

2.4 Periodic Characteristics

Wavelet analysis revealed multiple periodic oscillations in extreme precipitation indices [Figure 5: see original paper]. PRCPTOT showed significant periods of 7 years, 14 years, and 20 years, with the 14-year period being most prominent during the 1960s–1980s. Rx1day exhibited periods of 3 years, 7 years, and 14 years, with the 7-year period dominant during the 1970s–1990s. Rx5day displayed periods of 5 years, 14 years, and 20 years, with the 20-year period significant after 1990.

The CDD index showed periods of 7 years, 14 years, and 22 years, with the 14-year period prominent during the 1960s–1990s. Heavy precipitation indices (R95p, R99p) exhibited periods of 3-5 years and 14–17 years, with the 14–17 year cycle being particularly strong during the 1970s–2000s. These periodicities may be linked to large-scale climate oscillations such as the Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation.

2.5 Correlation Analysis

Principal component analysis revealed strong correlations among extreme precipitation indices . The first principal component explained 68.38% of the total variance, with high loadings on PRCPTOT (0.902), Rx5day (0.922), and R95p (0.908), indicating these indices represent the overall precipitation regime. The second component explained 13.07% of variance, primarily loading on CDD (0.777) and SDII (0.804), representing precipitation intensity and dry spell characteristics.

Correlation analysis showed that PRCPTOT was significantly correlated with Rx1day ($r=0.631$, $p<0.01$) and Rx5day ($r=0.922$, $p<0.01$). Heavy precipitation indices (R95p, R99p) were strongly correlated with Rx5day ($r=0.881$ and 0.844, respectively). The CDD index was negatively correlated with most other indices, particularly PRCPTOT ($r=-0.205$, $p<0.05$), confirming its representation of dry conditions.

3 Discussion

3.1 Impacts of Extreme Precipitation Changes

The decreasing trend in extreme precipitation indices has significantly affected Inner Mongolia’ s ecological and socioeconomic systems. Reduced precipitation has exacerbated drought conditions, particularly in the central and western regions. During the 2000s, severe droughts occurred in 2001, 2006, and 2007, affecting over 60% of the region’ s grasslands [41]. The increasing CDD has intensified desertification, with desertified land area expanding by 2.60×10 hm^2 during the 1990s [33].

Conversely, extreme precipitation events have caused severe flood disasters. In 1998, heavy rainfall in the northeastern region caused floods affecting 2.79×10 hm^2 of grassland [38]. In 2013, extreme precipitation events in the eastern region resulted in economic losses exceeding 2.70×10 yuan [33]. The contrasting impacts of decreasing mean precipitation and increasing precipitation extremes highlight the region’ s vulnerability to climate variability.

3.2 Adaptation Strategies

Given the observed trends in extreme precipitation, adaptation strategies should focus on: (1) strengthening drought monitoring and early warning systems, particularly in arid and semi-arid regions; (2) implementing water conservation measures and improving irrigation efficiency; (3) restoring grassland ecosystems to enhance resilience to climate extremes; and (4) developing integrated flood and drought management plans that account for spatial heterogeneity in precipitation trends.

The significant periodicities identified (7-year, 14-year, and 20-year cycles) provide a basis for decadal climate predictions and proactive adaptation planning. The strong correlations among extreme precipitation indices suggest that monitoring key indices like PRCPTOT and Rx5day can effectively track overall precipitation regime changes.

4 Conclusions

(1) Over the past 60 years, extreme precipitation indices in Inner Mongolia have exhibited significant decreasing trends, including PRCPTOT, Rx1day, Rx5day, R95p, and R99p. The CDD index showed a significant increasing trend, indicating more frequent and prolonged dry spells.

(2) Spatially, extreme precipitation indices decreased from the eastern and western regions toward the central area, with low-value centers in Hohhot, Ulanqab, and Xilingol. A significant mutation occurred around 1995, after which most indices entered a period of persistent reduction.

(3) Extreme precipitation indices exhibited multi-scale periodicities of 3–5 years, 14–17 years, and approximately 20 years. Strong correlations exist among most indices, except CDD, which was negatively correlated with wetness indicators.

(4) The changes in extreme precipitation have resulted in increased drought and wind disasters, grassland desertification, and reduced flood and low-temperature disasters. These findings underscore the need for region-specific adaptation strategies to mitigate climate risks in Inner Mongolia.

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