

Spatiotemporal Evolution Characteristics of Extreme Precipitation Events in the Loess Plateau from 1960 to 2023: Postprint

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Abstract

Under the trend of global warming, extreme climate events occur frequently on the Loess Plateau, and clarifying the spatiotemporal characteristics of extreme precipitation events on the Loess Plateau is of great significance for regional disaster prevention. Based on daily precipitation data from 111 meteorological stations on the Loess Plateau from 1960 to 2023, extreme precipitation events were identified by determining extreme precipitation thresholds using the Detrended Fluctuation Analysis (DFA) method, and characteristics of extreme precipitation events in the entire Loess Plateau and its ecological zones were analyzed using the Mann-Kendall test and other methods. The results show that: (1) The extreme precipitation thresholds at various meteorological stations on the Loess Plateau range from 27.4 to 89.1 mm, with 54% of stations having thresholds >50 mm. The average thresholds of each ecological zone range between 35.0 and 59.6 mm, showing a distribution pattern of low in the northwest and high in the southeast. (2) The precipitation amount and intensity of extreme precipitation events increase from $10.6 \text{ mm} \cdot \text{a}^{-1}$ and $33.0 \text{ mm} \cdot \text{d}^{-1}$ in the northwest to $71.5 \text{ mm} \cdot \text{a}^{-1}$ and $133.0 \text{ mm} \cdot \text{d}^{-1}$ in the southeast, respectively, while their occurrence frequency increases from $0.3 \text{ d} \cdot \text{a}^{-1}$ in the north to $0.8 \text{ d} \cdot \text{a}^{-1}$ in the south. The number of extreme precipitation days is closer to that of heavy rain days, particularly in the B2 subregion of the Loess Hilly Gully Region. (3) The Loess Highland Gully Region, Rocky Mountain Region, and Valley Plain Region are high-incidence areas for extreme precipitation events and should be designated as key areas for disaster prevention and control. (4) Over the past 64 years, extreme precipitation events have exhibited pronounced interannual variability, with an overall increase across the region, concentrated in July and August. (5) In the recent decade, the precipitation amount and frequency of extreme precipitation events in the Loess Highland Gully Region and Loess Hilly Gully Region have increased; the decreasing trend of extreme

precipitation events in Sandy Land and Agricultural Irrigation Areas has slowed, while abrupt changes and increases occurred in the Rocky Mountain Region and Valley Plain Region in 2020. The research findings provide a reference basis for disaster prevention and mitigation of extreme precipitation events in various ecological zones of the Loess Plateau.

Full Text

Spatiotemporal Evolution Characteristics of Extreme Precipitation Events on the Loess Plateau from 1960 to 2023

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Abstract: Under global warming, extreme climate events have become increasingly frequent on the Loess Plateau. Clarifying the spatiotemporal characteristics of extreme precipitation events is crucial for regional disaster prevention. Based on daily precipitation data from 111 meteorological stations across the Loess Plateau from 1960 to 2023, this study identifies extreme precipitation events by determining thresholds through detrended fluctuation analysis (DFA). The characteristics of these events across the entire plateau and its ecological regions are analyzed using the Mann-Kendall test and other methods. The results show that: (1) Extreme precipitation thresholds at meteorological stations range from 27.4 to 89.1 mm, with 54% of stations exceeding 50 mm. Average thresholds across ecological regions vary between 35.0 and 59.6 mm, exhibiting a spatial pattern of low values in the northwest and high values in the southeast. (2) The precipitation amount and intensity of extreme events increase from 10.6 mm · a⁻¹ and 33.0 mm · d⁻¹ in the northwest to 71.5 mm · a⁻¹ and 133.0 mm · d⁻¹ in the southeast, respectively, while their frequency rises from 0.3 d · a⁻¹ in the north to 0.8 d · a⁻¹ in the south. The number of extreme precipitation days closely aligns with heavy rain days, particularly in the loess hilly gully B2 sub-region. (3) The loess tableland gully region, earth-rocky mountainous region, and river valley plain region are identified as high-incidence areas for extreme precipitation events and should be prioritized for disaster prevention and control. (4) Over the past 64 years, extreme precipitation events have shown significant interannual variability, with an overall increasing trend concentrated in July and August. (5) In the last decade, the loess tableland gully and loess hilly gully regions have experienced increased precipitation amounts and frequencies of extreme events. Meanwhile, the declining trend in extreme precipitation events has slowed in sandy land and irrigated agricultural regions, while the

earth-rocky mountainous and river valley plain regions experienced abrupt increases in extreme precipitation events around 2020. These findings provide a reference basis for disaster prevention and mitigation of extreme precipitation events across different ecological regions of the Loess Plateau.

Keywords: extreme precipitation threshold; extreme precipitation events; temporal and spatial changes; ecological regionalization; Loess Plateau

1 Data and Methods

1.1 Study Area Overview

The Loess Plateau (33°41' ~41°16' N, 100°52' ~114°33' E) features complex terrain and variable climate, holding significant importance for China's socioeconomic development and ecological conservation. With elevations ranging up to 3000 m, the plateau exhibits a general topography that is higher in the northwest and lower in the southeast. It belongs to a typical continental monsoon climate zone characterized by concurrent rainfall and heat, with severely uneven spatial distribution of precipitation.

To investigate regional variations in geography, terrain, and climate, this study employs ecological regionalizations formulated according to National Development and Reform Commission requirements to analyze the distribution characteristics of extreme precipitation events. The ecological regionalizations include: loess tableland gully region (A), loess hilly gully region (B), earth-rocky mountainous and river valley plain region (D), and sandy land and irrigated agricultural region (C). Given substantial differences in terrain, climate, and other factors within each region, region A is further divided into A1 and A2 sub-regions using the Liupan Mountains as a boundary, while region B is divided into B1 and B2 sub-regions bounded by the southern edge of the Mu Us Desert.

[Figure 1: see original paper]

1.2 Data Sources and Processing

Precipitation data for this study were obtained from the China Meteorological Science Data Center (<http://data.cma.cn>). To ensure data integrity, meteorological stations with excessive missing data or insufficient observation years were excluded. Considering that surrounding areas may influence climate conditions in the Loess Plateau's border zones, 111 stations across the Loess Plateau and adjacent regions were ultimately selected (Fig. 1). Daily precipitation observations from 1960 to 2023 were compiled to establish stable and continuous precipitation time series.

1.3 Methods

1.3.1 Determination of Extreme Precipitation Threshold This study employs detrended fluctuation analysis (DFA) to determine extreme precipitation thresholds. The DFA method aims to identify a critical daily precipitation value that serves as the extreme precipitation threshold, satisfying the condition that when data points below the critical value remain unchanged, any rearrangement of data points above the critical value will not affect the long-range correlation exponent of the entire sequence.

For a precipitation sequence $\{x_i\}$ of length n ($i = 1, 2, \dots, n$), the DFA method determines the threshold through the following steps:

1. Calculate the maximum (x_{\max}) and minimum (x_{\min}) values of the sequence, then determine an intermediate point (x_c) as either the average ($(x_{\max} + x_{\min})/2$) or a value between the maximum and minimum.
2. Starting from the maximum value (x_{\max}), sequentially remove data points in intervals of d until $x = x_{\max} - k \cdot d$, where $k = 1, 2, \dots, (x_{\max} - x_c)/d$. This generates new sequences Y_j , where $J = 1, 2, \dots, (x_{\max} - x_c)/d$.
3. Starting from the minimum value (x_{\min}), sequentially remove data points in intervals of d until $x = x_{\min} + k \cdot d$, where $k = 1, 2, \dots, (x_c - x_{\min})/d$. This generates new sequences Y_j , where $J = (x_c - x_{\min})/d + 1, (x_c - x_{\min})/d + 2, \dots, (x_c - x_{\min})/d + (x_{\max} - x_c)/d$.
4. Calculate the long-range correlation exponent (D) for each new sequence Y_j and establish its relationship with interval J . For a precipitation sequence Y_j of length N ($j = 1, 2, \dots, N$), the long-range correlation exponent is computed as follows:
 - Calculate the cumulative deviation series: $y(j) = \sum_{i=1}^j (Y(i) - \bar{Y})$, where \bar{Y} is the sequence mean.
 - Divide the sequence into $N_s = \text{int}(N/s)$ non-overlapping sub-intervals of length s . To ensure no information loss, repeat the process from the sequence end, yielding $2N_s$ sub-intervals.
 - Fit each sub-interval v ($v = 1, 2, \dots, 2N_s$) using polynomial regression to obtain the local trend function $y(i)$.
 - Remove the trend from each sub-interval and calculate its mean variance: $F^2(s, v) = (1/s) \sum_{i=1}^s [y(i) - \bar{y}]^2$.
 - Compute the q -th order fluctuation function: $F_q(s) = \{(1/2N_s) \sum_{i=1}^{2N_s} [F^2(s, v)]^{(q/2)}\}^{1/q}$, where q takes any non-zero real number.
 - The scaling exponent α is obtained from the double logarithmic plot of $F_q(s)$ versus s , where α represents the slope of $\log_{10}(F_q(s))$ versus $\log_{10}(s)$.
5. When the variation of D for different precipitation sequences Y_j begins to stabilize and converge to the long-range correlation exponent of the original precipitation sequence, the corresponding J value is taken as the

data point index, and the precipitation value at this position is adopted as the extreme precipitation threshold.

1.3.2 Screening of Extreme Precipitation Events and Index Calculation

When daily precipitation at a station exceeds its extreme precipitation threshold, it is recorded as an extreme precipitation event. Thresholds are used to screen extreme precipitation events at each station, and annual extreme precipitation amount, days, and intensity are calculated. Additionally, five extreme precipitation indices defined and recommended by the World Meteorological Organization (WMO) are selected and calculated using RCLIMDEX 1.0 software to establish annual time series for each station. These indices are compared with the extreme precipitation event indicators determined based on the DFA thresholds.

1.3.3 Statistical Analysis Sen's slope estimator is a non-parametric trend estimation method that yields the median slope of a sequence. For a time series x_j and x_k ($j < k$), the slope between any two data points is calculated as $S_{jk} = (x_k - x_j)/(k - j)$. With $N = n(n-1)/2$ slope values, Sen's estimator is the median of all slopes: $S = S_{(1+N)/2}$ when N is odd, or $S = (S_{N/2} + S_{N/2+1})/2$ when N is even. The sign of S indicates trend direction: $S > 0$ indicates an upward trend, while $S < 0$ indicates a downward trend.

The Mann-Kendall test, widely used for trend and mutation detection in meteorological data due to its distribution-free nature, assesses trend significance through the standard normal statistic Z . The test statistic S measures the difference between upward and downward trends in the time series. When $|Z| \geq 1.64$ ($p < 0.05$), the trend is considered significant. Positive Z values indicate upward trends, while negative values indicate downward trends.

Mutation detection employs forward (UF) and backward (UB) sequences to identify abrupt changes. When UF or UB are positive, the sequence shows an upward trend; negative values indicate a downward trend. Intersection points between UF and UB curves within critical limits indicate mutation times.

The coefficient of variation (C) normalizes the dispersion of probability distributions to assess interannual variability. Calculated as $C = \sigma/\bar{x}$ (where σ is standard deviation and \bar{x} is mean), larger C values indicate greater interannual variation. Variability is classified as weak ($C \leq 0.1$), moderate ($0.1 < C \leq 0.2$), or strong ($C > 0.2$).

2 Results

2.1 Extreme Precipitation Thresholds

The spatial distribution of extreme precipitation thresholds across the Loess Plateau from 1960 to 2023 follows a pattern similar to mean annual precip-

itation, characterized by low values in the northwest and high values in the southeast. Station-level thresholds range from 27.4 to 89.1 mm, with high values concentrated in the southeastern plateau where 54% of stations exceed the national heavy rain standard of $50 \text{ mm} \cdot \text{d}^{-1}$.

Significant differences exist among ecological regions. The sandy land and irrigated agricultural region (C) shows the smallest thresholds, with no stations exceeding $50 \text{ mm} \cdot \text{d}^{-1}$. The A2 and B2 sub-regions have average thresholds approaching 50 mm (51.6 mm and 50.6 mm, respectively). The loess tableland gully region (A) exhibits the largest range (35.7–89.1 mm) and highest average threshold (59.6 mm). The loess hilly gully region (B) shows thresholds ranging from 41.8 to 62.6 mm with an average of 57.1 mm.

[Figure 2: see original paper]

2.2 Spatial Distribution Characteristics of Extreme Precipitation Events

Based on the DFA-derived thresholds, three extreme precipitation indicators—amount, days, and intensity—reveal distinct spatial patterns. Extreme precipitation amount and intensity generally increase from northwest to southeast, while extreme precipitation days follow a north-south gradient. The spatial distribution of extreme precipitation amount closely resembles that of annual precipitation, with the 400 mm isohyet serving as a boundary: areas northwest of this line receive less than $25 \text{ mm} \cdot \text{a}^{-1}$ of extreme precipitation [Figure 3: see original paper].

Extreme precipitation days increase from $0.3 \text{ d} \cdot \text{a}^{-1}$ in the north to $0.8 \text{ d} \cdot \text{a}^{-1}$ in the south, with the fewest days occurring in the northwestern plateau. Extreme precipitation intensity shows low values in the western plateau and high values in the southeast.

Among the five WMO extreme precipitation indices, CWD (consecutive wet days), R25mm (heavy rain days), R50mm (storm rain days), RX1day (maximum 1-day precipitation), and RX5day (maximum 5-day precipitation) generally increase from northwest to southeast, except for CWD. R25mm, R50mm, RX1day, and RX5day align well with annual precipitation distribution patterns. Only 8% of stations record $\text{R50mm} \geq 1 \text{ d} \cdot \text{a}^{-1}$, indicating that extreme precipitation events in the Loess Plateau are characterized by high amounts, high frequency, and strong intensity.

Comparison between DFA-derived indicators and WMO indices reveals that RX1day is far below extreme precipitation intensity across all regions, with mean differences exceeding 20 mm. R25mm and R50mm are closer to extreme precipitation days, particularly in the loess hilly gully B2 sub-region where the mean extreme precipitation days (0.48 d) closely approaches R50mm (0.50 d).

2.3 Temporal Variation Characteristics of Extreme Precipitation Events

2.3.1 Trend Changes Extreme precipitation amount, days, and intensity show similar trends across stations. At the 0.05 significance level, 54% of stations exhibit significant upward trends in extreme precipitation amount [Figure 4: see original paper]. Changes in extreme precipitation days directly reflect frequency variations, with 52% of stations showing increasing trends. The mean extreme precipitation intensity is $66.9 \text{ mm} \cdot \text{d}^{-1}$, exceeding China's heavy rain intensity standard. More stations show increasing intensity (52%) than decreasing (48%).

The coefficients of variation for extreme precipitation amount and days are 0.58 and 0.54, respectively, indicating moderate interannual variability and significant fluctuations. Extreme precipitation events concentrate in summer, particularly July and August [Figure 5: see original paper]. Over the past 64 years, more than 50% of stations show decreasing CWD trends, with 17 stations significant at $p < 0.05$. Regional R25mm and R50mm show increasing trends, with R25mm increasing at $0.009 \text{ d} \cdot \text{a}^{-1}$ and 60% of stations trending upward.

2.3.2 Mutation Analysis Mann-Kendall mutation tests reveal that extreme precipitation amount, frequency, and intensity across the entire Loess Plateau fluctuate near zero without clear mutation points. However, distinct patterns emerge across ecological regions [Figure 6: see original paper].

The A1 sub-region shows a downward mutation in extreme precipitation amount around 1980, followed by an upward mutation in 2010 and subsequent increase. The A2 sub-region exhibits a decreasing mutation around 2000, with slowing decline thereafter. The B1 sub-region shows an upward mutation around 2010, while B2 displays fluctuating decreases after a 1990s mutation. Region C experienced a mutation around 1995 with persistent fluctuating decline. Region D shows an upward mutation around 2020.

For extreme precipitation days, A1 remains in the negative zone post-1980s, while A2 mutated from decreasing to increasing around 2000. B1 mutated from low to high around 2010, and B2 shows significant reduction after a 1990s mutation. Region C demonstrates decreasing trends since the 1980s, while Region D mutated to increase around 2020.

Extreme precipitation intensity shows multiple intersections between UF and UB curves across all regions, with A1 and A2 sub-regions exhibiting particularly complex patterns.

3 Discussion

3.1 Spatial Distribution of Extreme Precipitation Events

Extreme precipitation events are difficult to predict, and their assessment complexity increases on the Loess Plateau due to substantial topographic and climatic variations. This study reveals that southern regions (loess tableland gully, earth-rocky mountainous, and river valley plain regions) are more vulnerable to extreme precipitation impacts.

The loess tableland gully region exhibits high extreme precipitation frequency and intensity. Combined with fragmented terrain, deep and loose soil layers, and poor erosion resistance, this region constitutes a primary source of sediment for the Yellow River. Under extreme precipitation conditions, various erosion processes intensify, generating substantial sediment and triggering severe erosion disasters. Although the earth-rocky mountainous and river valley plain region has relatively good vegetation cover and underlying surface conditions, it records the highest incidence and intensity of extreme precipitation events among all ecological regions, significantly increasing flood risks. For example, continuous heavy precipitation in October 2021 caused the Beiluo River to breach its banks in Dali County, Weinan City, affecting 49,100 people and inundating 2,390 hectares of cropland.

Given that extreme precipitation disasters result from combined natural and socioeconomic factors, systematic risk assessments are needed to further understand disaster mechanisms across regions. Previous studies at provincial or soil erosion type zone scales show consistent patterns: Yang et al. found decreasing extreme precipitation in southwestern Gansu's loess plateau; Li et al. observed increasing heavy precipitation in northern Shaanxi; Li et al. reported significant extreme precipitation in central and southwestern parts of the plateau's water-wind erosion crisscross region. These findings align with our results for corresponding sub-regions and periods.

While WMO extreme precipitation indices facilitate international comparisons, some cannot characterize true extreme events. For instance, RX5day reflects precipitation persistence but may not meet extreme event criteria. Our comparison shows that mean annual RX1day across all regions falls below DFA-derived thresholds, indicating extreme events occur infrequently in most years. The close match between extreme precipitation days and R50mm in the loess hilly gully B2 sub-region suggests WMO indices can provide simple descriptions of extreme events in this area.

3.2 Temporal Changes of Extreme Precipitation Events

Unlike widespread temperature increases, long-term evolution of extreme precipitation exhibits more complex spatiotemporal patterns. All ecological regions showed decreasing trends in the 1980s, with region C experiencing fluctuating decline after a 1995 mutation. Since the 2000s, large-scale ecological restoration

projects have significantly increased vegetation coverage on the Loess Plateau, affecting seasonal precipitation distribution and potentially influencing extreme precipitation events, though the relationship requires further investigation integrating multiple factors and long-term observations.

Since the 21st century, substantial greenhouse gas emissions have driven warming and humidification of the Loess Plateau climate, affecting seasonal water cycles and increasing extreme precipitation probability. The overall increase in extreme precipitation events primarily results from recent climate warming and human activity interference.

While this study examines historical data from 1960-2023, future evolution of extreme precipitation events and the specific impacts of climate change and human activities require further research.

4 Conclusions

This study investigates spatiotemporal variations of extreme precipitation events on the Loess Plateau from 1960 to 2023, yielding the following conclusions:

1. **Spatial distribution of extreme precipitation thresholds:** Thresholds range from 27.4 to 89.1 mm across stations, with 54% exceeding 50 mm. At the ecological region scale, thresholds vary from 35.0 mm to 59.6 mm, showing a clear northwest-southeast gradient. The loess tableland gully A2 sub-region and earth-rocky mountainous region have the highest average thresholds (59.6 mm and 57.1 mm, respectively).
2. **Spatial patterns of extreme precipitation events:** Extreme precipitation amount and intensity increase from northwest to southeast, while extreme precipitation days show a north-south gradient. The loess tableland gully region and earth-rocky mountainous and river valley plain region are high-incidence areas requiring prioritized disaster prevention.
3. **Temporal trends:** Extreme precipitation events exhibit significant interannual variability with an overall increasing trend. Regional extreme precipitation amount and intensity have increased at rates of $0.128 \text{ mm} \cdot \text{a}^{-1}$ and $0.009 \text{ mm} \cdot \text{d}^{-1} \cdot \text{a}^{-1}$, respectively. In the last decade, the loess tableland gully and loess hilly gully regions have shown increased precipitation amounts and frequencies, while region C' s declining trend has slowed and region D experienced an abrupt increase around 2020.

These findings provide scientific support for disaster risk reduction and climate adaptation strategies across the Loess Plateau' s ecological regions.

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