

Analysis of Spatiotemporal Evolution Characteristics of Extreme Climate Events in Xinjiang Under Climate Warming and Wetting: Postprint

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Abstract

Based on daily meteorological data from 1982 to 2020, this study employs trend analysis, correlation analysis, Hurst exponent, and relative importance methods to analyze the spatiotemporal variation characteristics and patterns of extreme climate events in Xinjiang. The results indicate that all extreme temperature indices in Xinjiang exhibit a warming trend, with the proportion of stations showing warming trends for different extreme temperature indices ranging from 50.98% to 100%. Cold indices demonstrate greater warming than warm indices, and spatially, the warming trend in Southern Xinjiang is more pronounced than in Northern Xinjiang. Except for the Consecutive Dry Days index (CDD), extreme precipitation indices overall show an insignificant upward trend, with the proportion of stations ranging from 61.76% to 85.29%. Increases in extreme temperature frequency indices, total precipitation on rainy days, and the number of light and moderate rain days contribute relatively significantly to the warming and wetting trend in Xinjiang. Except for the Ice Days index (ID) and the Simple Daily Intensity Index (SDII), changes in other extreme climate indices are sustainable, and the increase in extreme precipitation and the warming trend of most extreme temperature indices, particularly cold indices, are more evident in high-altitude regions.

Full Text

New Characteristics of Spatiotemporal Evolution of Extreme Climate Events in Xinjiang Under the Background of Warm and Humid Climate

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Abstract

Based on daily meteorological data from 1982 to 2020, this study analyzed the spatiotemporal variability characteristics of extreme climate events in Xinjiang using trend analysis, correlation analysis, Hurst index, and relative importance methods. The results indicate that all extreme temperature indices in Xinjiang exhibited warming trends, with 50.98%-100% of stations showing increasing trends for different indices. Cold indices demonstrated stronger warming than warm indices, and the warming trend was more pronounced in southern Xinjiang than in northern Xinjiang. Except for the continuous drought index (CDD), the overall extreme precipitation indices showed non-significant upward trends, with 61.76%-85.29% of stations exhibiting increases. The increase in extreme temperature frequency indices, total precipitation on wet days, and the number of light and moderate rain days contributed relatively significantly to Xinjiang's warming and humidification trend. Except for icing days (ID) and annual mean precipitation intensity on wet days (SDII), changes in other extreme climate indices were sustainable, and the increase in extreme precipitation and the warming trend of most extreme temperature indices—especially cold indices—were more pronounced in high-altitude regions.

Keywords: warm and humid climate; extreme climate; spatiotemporal characteristics; altitude dependence; Xinjiang

1 Introduction

Global warming-dominated climate change has profoundly impacted climate system stability, leading to frequent extreme events. The IPCC Sixth Assessment Report indicates that future global climate will continue warming, with increasing heatwaves, heavy precipitation, and complex, abrupt extreme events that adversely affect regional ecological environments and human production activities. Therefore, understanding extreme climate event trends is crucial for sustainable regional ecosystem development and has attracted increasing attention from researchers worldwide.

Studies show that over the past half-century, the frequency, intensity, duration, and spatial extent of global extreme precipitation and temperature events have increased dramatically, with more sensitive changes. Consistent conclusions indicate that warm-index-related extreme events are increasing while cold-index events are decreasing significantly, with extreme precipitation intensity and frequency both increasing. However, due to topography, atmospheric circulation, and other factors, regional extreme climate changes vary significantly, showing unique distribution and change patterns.

Xinjiang, located in northwestern China, has an extremely fragile ecological environment sensitive to climate change. Recent frequent extreme events have significantly impacted this vulnerable ecosystem. Previous research shows that from 1961 to 2010, both frequency and intensity of extreme temperatures in Xinjiang increased, with a warming rate of $0.4^{\circ}\text{C} \cdot (10\text{a})^{-1}$, higher than the national average. Seasonally, winter warming in Xinjiang exceeds summer warming. Frequent extreme precipitation events have caused significant humidification, though with substantial spatial differences: extreme precipitation increased significantly in northern Xinjiang and northern southern Xinjiang, while drought intensified in eastern and southern regions. Additionally, studies indicate that circulation systems such as the Arctic Oscillation and Southern Oscillation significantly affect Xinjiang's climate, with different regions showing varying responses.

While previous studies have yielded important results on Xinjiang's extreme climate events, most have discussed extreme temperature or precipitation separately, with limited research on altitude dependence and sustainability of extreme event changes. Therefore, this study analyzes spatiotemporal variation characteristics of 12 extreme climate indices from 102 meteorological stations, exploring altitude dependence to provide decision-making references for disaster prevention, mitigation, and sustainable regional development.

2 Study Area and Methods

2.1 Study Area Overview

Xinjiang is located in central Eurasia, covering 1.6649 million km^2 as a major component of China's northwest arid and semi-arid regions. Elevation ranges from -190 m to 7,680 m, with complex and diverse terrain: the Altai Mountains in the north, Kunlun Mountains in the south, and the Tianshan Mountains in the center, creating a "three mountains surrounding two basins" pattern. The Tianshan Mountains divide Xinjiang into southern and northern regions (Fig. [Figure 1: see original paper]). The inland location far from oceans creates a typical temperate continental climate with annual mean temperatures of $9\text{--}12^{\circ}\text{C}$, large diurnal temperature ranges, and long annual sunshine hours, making it rich in solar energy resources. Precipitation is scarce and concentrated, with average annual precipitation of approximately 165 mm. The region's massive mountains intercept water vapor, creating much higher precipitation in mountainous areas than plains, with windward slopes receiving more than leeward slopes. Xinjiang has numerous river systems primarily fed by glacier and perennial snowmelt.

2.2 Data Sources and Processing

Meteorological data included daily maximum temperature, minimum temperature, and precipitation from 102 Xinjiang meteorological stations (1982–2020) from the National Meteorological Science Data Center. After removing outliers, RClimDex software calculated extreme climate indices. This study selected 12

extreme climate indices from the ETCCDI index system, comprehensively considering intensity, frequency, and duration of extreme climate events (Table). DEM data for Xinjiang and Chinese administrative boundary data were obtained from the National Geographic Information Resources Directory Service System.

2.3 Methods

2.3.1 Trend Analysis Linear trend analysis calculated extreme climate event trends:

$$Slope = \frac{n \sum iT_i - \sum i \sum T_i}{n \sum i^2 - (\sum i)^2}$$

where *Slope* is the linear regression equation slope; *n* is the time series length; *i* is the year index (*i* = 1, 2, ..., *n*); and *T_i* is the extreme climate index value for year *i*. A positive slope indicates an increasing trend, while negative indicates decreasing.

2.3.2 Hurst Index Analysis Hurst index analysis quantitatively describes persistence characteristics of time series trends, a nonlinear scientific prediction method. For time series *N*, for any τ , define the mean sequence:

$$\delta(t, \tau) = \frac{1}{\tau} \sum_{t=1}^{\tau} T(t)$$

The cumulative deviation is:

$$X(t, \tau) = \sum_{u=1}^t (T(u) - \delta(t, \tau)), \quad 1 \leq t \leq \tau$$

The range *R* is calculated from the difference between maximum and minimum cumulative deviations:

$$R(\tau) = \max_{1 \leq t \leq \tau} X(t, \tau) - \min_{1 \leq t \leq \tau} X(t, \tau)$$

The standard deviation *S* is:

$$S(\tau) = \sqrt{\frac{1}{\tau} \sum_{t=1}^{\tau} (T(t) - \delta(t, \tau))^2}$$

The Hurst exponent *H* is obtained from *R/S* analysis. When $H < 0.5$, the time series future trend is opposite to the past (anti-persistence). When $H = 0.5$,

the series is random without long-term correlation. When $H > 0.5$, the series is persistent with long-term correlation, where past increasing trends indicate future increases.

2.3.3 Correlation Analysis Pearson correlation analysis reveals relationships between geographic elements. For variables x and y with time series x_i and y_i ($i = 1, 2, \dots, n$), the correlation coefficient is:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}}$$

The correlation coefficient r ranges from -1 to 1, with larger absolute values indicating stronger correlation.

2.3.4 Relative Importance Calculation Relative importance analysis quantified contributions of extreme climate indices to mean annual temperature (MAT) and annual total precipitation (AP). Implementation: first normalize factors, then use multiple regression to calculate explanation degrees. The “relaimpo” package in R completed this analysis, decomposing model R^2 into each factor’s contribution.

3 Results

3.1 Temporal Variation Characteristics of Extreme Climate Indices

Among warm indices, TN90p and TX90p showed significant increasing trends ($P < 0.05$), with rates of $2.58 \text{ d} \cdot (10\text{a})^{-1}$ and $1.62 \text{ d} \cdot (10\text{a})^{-1}$, respectively. TN90p showed a more obvious upward trend, with both indices’ minimum values appearing in 1984. Cold indices TN10p and TX10p showed significant decreasing trends ($P < 0.05$), with rates of $-3.76 \text{ d} \cdot (10\text{a})^{-1}$ and $-3.21 \text{ d} \cdot (10\text{a})^{-1}$, respectively. TX10p’s decreasing trend was more significant than TN10p’s. Except for TN10p, other indices passed significance tests. The lowest values of TX10p and TN10p appeared in 2010 and 2009, respectively. Among other indices, extreme temperature values showed significant increasing trends: warm spell duration (WSDI) increased at $4.75 \text{ d} \cdot (10\text{a})^{-1}$, cold spell duration (CSDI) decreased at $-1.35 \text{ d} \cdot (10\text{a})^{-1}$, and diurnal temperature range (DTR) decreased at $-0.16^\circ\text{C} \cdot (10\text{a})^{-1}$. In summary, Xinjiang’s extreme temperature indices showed significant warming trends, with cold index warming most pronounced, consistent with national studies.

Overall, wet indices in Xinjiang showed varying degrees of upward trends during the study period (Fig. [Figure 3: see original paper]), indicating increased extreme precipitation events. The dry index CDD showed a decreasing trend at $-2.21 \text{ d} \cdot (10\text{a})^{-1}$, suggesting gradually decreasing continuous drought events. Among wet indices, extreme precipitation intensity indices (Rx1day, Rx5day)

and frequency indices (R10mm, R25mm) showed significant upward trends with rates increasing from north to south. PRCPTOT showed a non-significant upward trend, while SDII showed a non-significant downward trend, reflecting increased precipitation concentration and higher flood risk.

3.2 Spatial Variation Characteristics

Spatial heterogeneity was evident in extreme temperature index trends across stations (Fig. [Figure 4: see original paper]). Stations with significant increasing trends in warm indices TN90p and TX90p were mainly distributed near the Tianshan Mountains, southwestern southern Xinjiang, and northern northern Xinjiang, accounting for 74.51% and 71.58% of stations, respectively. TX90p showed obvious increases east of the Tianshan Mountains, with decreasing areas concentrated in northern Xinjiang. TN90p showed similar but more concentrated decreasing patterns, with expanded increasing areas in southern Xinjiang and convergence zones between northern Xinjiang and Tianshan Mountains. TX10p and TN10p showed significant decreases at 99.02% and 95.10% of stations, respectively, with mountain stations showing higher decreasing rates than plain areas. Other indices showed opposite distribution patterns between increasing and decreasing stations, with change rates decreasing from west to east.

For extreme precipitation indices (Fig. [Figure 6: see original paper]), Rx1day, Rx5day, and PRCPTOT showed similar spatial patterns, with rates generally decreasing from west to east. Stations with significant increasing trends were mainly in northwestern Xinjiang, accounting for 85.29%, 75.49%, and 76.47% respectively. R10mm and R25mm showed increasing trends at 68.63% and 62.63% of stations, mainly north of the Tianshan Mountains. SDII showed increasing trends at 90.20% of stations, with significant increases only in western Xinjiang. The dry index CDD showed decreasing trends at 79.41% of stations, with only the northern Tarim Basin showing increasing trends. Overall, extreme precipitation events in Xinjiang increased during 1982–2020, with more pronounced increases in mountainous than plain areas.

3.3 Contribution Rates of Extreme Climate Indices

Correlation analysis between extreme temperature indices and mean annual temperature (MAT) showed that all correlations passed significance tests except for DTR. Extreme temperature frequency indices showed higher correlations with MAT (absolute correlation coefficients > 0.8) than intensity indices. Relative importance analysis (Table) revealed that low-temperature frequency indices contributed more to MAT than high-temperature frequency indices. TN10p and TX10p showed the highest relative importance, while TXx and TNx showed lower contributions. Frequency indicators demonstrated greater relative importance and higher contribution rates than intensity indicators.

For precipitation, all extreme precipitation indices showed significant positive

correlations with annual precipitation (AP) (Fig. [Figure 8: see original paper]). Correlation coefficients for R10mm, Rx1day, and Rx5day with AP exceeded 0.8, while PRCPTOT showed the highest correlation ($r = 0.98$). Relative importance analysis (Table) ranked contributions as: PRCPTOT > R10mm > Rx5day > Rx1day > R25mm > SDII > CWD. R25mm showed the smallest relative importance (6.29%).

3.4 Elevation Dependence of Extreme Climate Changes

Elevation dependence of extreme indices is shown in Table . The warming rate of TX10p showed significant negative correlation with elevation, indicating warming intensity decreases with altitude. Other warm indices (TX90p, TN90p) showed positive correlations with elevation, though not significant. Among cold indices, TN10p showed significant negative correlation with elevation, indicating faster decrease rates at higher altitudes, reflecting accelerated warming with elevation. TXn showed significant positive correlation, suggesting higher altitudes experience greater increases in daily maximum temperature minima.

For precipitation, all extreme precipitation indices except CDD showed positive correlations with elevation, with Rx1day, Rx5day, and R25mm passing significance tests. This indicates these extreme precipitation indices accelerate with elevation, showing significant positive elevation dependence. CDD showed non-significant negative correlation, reflecting more pronounced decreases in continuous dry days at high altitudes.

4 Discussion

This study analyzed 12 extreme climate indices to characterize Xinjiang's extreme climate events from 1982-2020. Results show increasing high-temperature events, decreasing low-temperature events, and extreme precipitation increases concentrated in mountainous areas, northern and western Xinjiang. Night-time temperatures (TN10p, TN90p) increased more than daytime temperatures (TX10p, TX90p), indicating greater nighttime warming contributions to overall temperature increases. Previous research shows asymmetric land surface warming, with nighttime warming rates 1.5-2 times daytime rates, possibly related to cloud cover, solar radiation, soil moisture, and atmospheric circulation changes. Increased cloud cover reduces daytime shortwave radiation while intercepting nighttime longwave radiation, making it a key factor.

Regional differences in extreme climate events are significant. The largest daytime temperature change rates occur in the Tianshan Mountains, while nighttime temperature and other index changes are most pronounced in southern Xinjiang and Tianshan areas. The Tianshan Mountains block winter monsoons, potentially reducing cold wave impacts south of the range in autumn and winter, causing more obvious warming. Additionally, scarce precipitation and strong potential evaporation south of the Tianshan Mountains amplify extreme index warming.

Overall extreme precipitation index changes were non-significant. PRCPTOT showed non-significant upward trends, indicating non-significant total precipitation increases. The increase in PRCPTOT and decrease in CDD confirm alleviated drought conditions, consistent with previous Xinjiang dry-wet transition research. This study found more pronounced extreme precipitation increases in mountainous versus plain areas, consistent with other research, likely due to topographic blocking and lifting causing stronger vertical airflow.

Spatially, warm indices showed broad increasing trends while cold indices decreased widely, with warm index increases concentrated in southern Xinjiang. Drought events gradually decreased, with 61.76%–85.29% of stations showing increasing trends in extreme precipitation indices except CDD. Extreme temperature frequency indices contributed more to mean temperature increases, while total precipitation on wet days and light/moderate rain days contributed more to precipitation increases.

Correlation analysis revealed good relationships between extreme climate indices and mean annual temperature/precipitation. Extreme temperature frequency indices (TX90p, TN90p, TX10p, TN10p) showed the best relative importance. Extreme precipitation frequency and intensity indices (PRCPTOT, R10mm) showed good importance. Most extreme climate indices showed sustainable changes, with extreme temperature indices demonstrating stronger persistence (higher Hurst values) than precipitation indices, possibly due to greater stability and lower variability.

Elevation dependence analysis revealed accelerated warming of most extreme temperature indices, especially cold indices, at higher altitudes. Pepin et al. [17] noted warming rates increase with elevation, consistent with our results. Yao et al. [12] found precipitation increases in China's arid regions accelerate with elevation, matching our significant positive elevation dependence findings for most extreme precipitation indices. However, uneven meteorological station distribution in Xinjiang, particularly in western Tianshan areas, necessitates enhanced station construction.

Hurst index analysis indicates future high-temperature indices will continue increasing, low-temperature indices decreasing, and precipitation maintaining an upward trend with increasing extreme precipitation probability, consistent with Li et al. [35]. These results suggest future risks of increasing extreme high-temperature and flood disasters in Xinjiang, warranting attention from relevant departments.

5 Conclusions

- 1) Most warm indices (TX90p, TN90p) showed significant increasing trends, while all cold indices except TN10p showed significant decreasing trends. Extreme precipitation events showed non-significant changes overall.
- 2) Spatially, warm indices increased widely while cold indices decreased.

Warm index increases were concentrated in southern Xinjiang. Drought events gradually decreased, with 61.76%-85.29% of stations showing increasing trends in extreme precipitation indices except CDD. Extreme temperature frequency indices contributed more to mean temperature increases, while total precipitation on wet days and light/moderate rain days contributed more to precipitation increases.

- 3) Correlation analysis revealed good relationships between extreme climate indices and mean annual temperature/precipitation. Extreme temperature frequency indices showed the best relative importance. Extreme precipitation frequency and intensity indices showed good importance. Most extreme climate indices showed sustainable changes, with extreme temperature indices demonstrating stronger persistence than precipitation indices.
- 4) Elevation dependence analysis revealed accelerated warming of most extreme temperature indices, especially cold indices, at higher altitudes. Extreme precipitation indices showed significant positive elevation dependence, with changes accelerating at higher elevations.

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