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Rainfall and extreme rainfall characteristics in southern Xinjiang from 1961 to 2022 (postprint)

Authors: Alim Erkin, Li Ruqi, Nurzat Abdukeyum, Mayire Aihaiti, Xirenayi Tiliwaldi

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Abstract

Using daily rainfall data from 45 national meteorological observation stations in southern Xinjiang for the period 1961–2022, this study analyzed the spatial-temporal distribution and variation characteristics of rainfall, determined the threshold for extreme rainfall, and examined the characteristics of extreme rainfall. The results show that: (1) Over the past 62 years, the region with the greatest annual mean rainfall and the fastest increase in southern Xinjiang has been the mid-mountain belt at elevations of 1,500–2,500 m, with an increasing rate of 5.4 mm per decade. This increase is mainly manifested in the growing number of rainy days, especially days with heavy rainfall, with a larger contribution from the increase in rainfall amount associated with extraordinarily heavy rainstorms and above. (2) By comparative analysis of the percentile method results, the 99th percentile was identified as the threshold criterion for extreme rainfall in southern Xinjiang, with threshold values ranging from 14.1 to 35.4 mm. Thresholds in the western mountainous areas and along the mountain margins are higher than those in the desert areas of the eastern basin. The extreme rainfall threshold has been increasing at a

Full Text

Characteristics of Rainfall and Extreme Rainfall in Southern Xinjiang from 1961 to 2022

Alim·ARKEN[1], LI Ruqi[2], Nurzat·ABDUKEYUM[1], Mayra·AHAT[1], Xerinay·TILIWALDI[1]

[1]Kashgar Meteorological Bureau, Kashgar 844000, Xinjiang, China
[2]Xinjiang Meteorological Observatory, Urumqi 830002, Xinjiang, China

Abstract

Using daily rainfall data from 45 national meteorological observation stations in southern Xinjiang from 1961 to 2022, this study analyzed the spatiotemporal distribution and variation characteristics of rainfall, determined extreme rainfall thresholds, and investigated extreme rainfall characteristics. The results show that: (1) Over the past 62 years, the region with the highest and most rapidly increasing annual average rainfall in southern Xinjiang has been located in the middle mountain belt at an altitude of 1500–2500 m, with a growth rate of 5.4 mm $\cdot$ $(10a)^{-1}$. This increase is mainly reflected in the greater number of rainfall days, particularly large-scale rainfall days, while the increase in heavy-rainstorm-level rainfall and above is especially pronounced. (2) Based on a comparative analysis using the percentile method, the 99th percentile was identified as the threshold for extreme rainfall in southern Xinjiang, corresponding to 14.1–35.4 mm. Thresholds in the western and mountain-adjacent regions are higher than those in the eastern basin-desert areas, and the extreme rainfall threshold has increased at a rate of 0.7 mm $\cdot$ $(10a)^{-1}$. Stations with the most rapid increases are primarily located in the mountainous areas of Kashgar, western Hotan, and northern Bayingol Mongolian Autonomous Prefecture. (3) Over the past 62 years, the number of extreme rainfall events in southern Xinjiang has generally ranged from 10–20 times, while in the Tianshan Mountains, events can exceed 20 times. Extreme rainfall events have increased in frequency at a rate of 0.9 events $\cdot$ $(10a)^{-1}$.

Keywords: precipitation; extreme rainfall; spatiotemporal characteristics; changing trends; southern Xinjiang

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1. Data and Methods

1.1 Data and Sources Southern Xinjiang generally refers to the area south of the Tianshan Mountains and north of the Kunlun Mountains, including Kashgar Prefecture, Kizilsu Kirghiz Autonomous Prefecture (referred to as Kezhou), Hotan Prefecture, Aksu Prefecture, and Bayingol Mongolian Autonomous Prefecture (referred to as Bazhou). For this analysis, the Kumishi station in Turpan City, which is climatologically closer to southern Xinjiang, was also included. The 45 national meteorological stations in southern Xinjiang [Figure 1: see original paper] have altitudes predominantly between 800–1500 m, with most stations established in the 1950s–1960s. Three stations exceed 2000 m: Wuqia (2177.5 m), Bayinbuluke (2459.9 m), and Taxkorgan (3090.2 m), with Turgart station reaching 3507.4 m.

This study utilized daily precipitation and temperature observation data from 20:00 to 20:00 BST for 45 stations in southern Xinjiang from 1961 to 2022. Based on operational experience, precipitation phase was determined using a daily minimum temperature criterion. This analysis focuses exclusively on rainfall, excluding snow or sleet. Data were obtained from the Xinjiang Meteoro-

logical Information Center, having undergone rigorous quality control to ensure reliability and continuity.

Following Xinjiang precipitation standards [1], daily rainfall was classified into seven levels: trace rain (0.1–0.2 mm), light rain (0.3–6.0 mm), moderate rain (6.1–12.0 mm), heavy rain (12.1–24.0 mm), rainstorm (24.1–48.0 mm), heavy rainstorm (48.1–96.0 mm), and extreme rainstorm (>96.0 mm).

1.2 Research Methods **Trend Analysis:** For meteorological element time series from 1961 to 2022, a simple linear regression model $y_i = a + bt_i$ was established, where y_i represents the annual meteorological element value, t_i is the year, a is the regression constant, b is the regression coefficient estimated via least squares, and n is the study period length. The linear trend rate is expressed as b.

Percentile Method for Extreme Rainfall Thresholds: Following common practice, extreme rainfall thresholds were defined using the percentile method [2]. Daily rainfall values for each station were sorted in ascending order for each year, and a specific percentile value was selected as the threshold. When daily rainfall exceeded this threshold, it was recorded as an extreme rainfall event. To determine appropriate thresholds for southern Xinjiang, the 95th, 97th, 99th, and 99.9th percentiles were compared. The 99th percentile was ultimately selected as the standard for extreme rainfall thresholds in southern Xinjiang.

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2. Results

2.1.1 Annual Rainfall Change Trends The 62-year average annual rainfall in southern Xinjiang was 62.1 mm, with 23 years (37% of the total) exceeding this average. Linear regression analysis reveals a statistically significant increasing trend at the 5% level, with a rate of 5.4 mm $\cdot$ $(10\text{a})^{-1}$. Annual rainfall increased by 33.5 mm over the study period.

2.1.2 Graded Rainfall Days Change Characteristics Analysis of rainfall day proportions shows that micro-rain days (0.1–0.2 mm) decreased significantly, accounting for 0.02%–0.22% of total rainfall days [Figure 3: see original paper]. Light rain days (0.3–6.0 mm) showed a slight increasing trend, comprising 10.1%–20.8% of days. Moderate rain days (6.1–12.0 mm) increased, representing 4.4%–9.8% of days. Heavy rain days (12.1–24.0 mm) showed a significant increasing trend, accounting for 1.3%–5.9% of days. Rainstorm days (24.1–48.0 mm) increased significantly, comprising 0.2%–2.1% of days and passing the 5% significance level. Heavy rainstorm days (48.1–96.0 mm) also increased significantly, representing 0%–1.0% of days. Extreme rainstorm days (>96.0 mm) increased significantly, accounting for 0%–0.6% of days.

These findings indicate that while micro-rain days are decreasing, days with heavy rain and above are increasing significantly, with heavy rain days showing the most pronounced increase. Southern Xinjiang's "wettening"trend is primarily driven by increases in large-scale rainfall events.

2.1.3 Graded Rainfall Amount Change Characteristics Micro-rainfall contributions (0.1–0.2 mm) decreased, averaging 1.3 mm and representing 0.02%–0.22% of total rainfall [Figure 4: see original paper]. Light rainfall contributions (0.3–6.0 mm) also decreased, averaging 135.2 mm and accounting for 10.1%–20.8% of total rainfall. Moderate rainfall (6.1–12.0 mm) decreased, averaging 195.5 mm and comprising 21.5% of total rainfall. Heavy rainfall (12.1–24.0 mm) decreased, averaging 336.4 mm and representing 12.0%–35.4% of total rainfall. Rainstorm contributions (24.1–48.0 mm) increased, averaging 602.0 mm and accounting for 23.1%–38.7% of total rainfall. Heavy rainstorm contributions (48.1–96.0 mm) increased, averaging 718.1 mm and representing 24.6%–49.7% of total rainfall.

These results demonstrate that contributions from rainfall events below 48.0 mm (rainstorm and below) are decreasing, with smaller magnitude events showing greater declines. The increase in total rainfall is primarily attributable to larger daily rainfall events, particularly those exceeding 96.0 mm.

2.1.4 Spatial Distribution of Annual Average Rainfall The spatial distribution of annual average rainfall [Figure 5: see original paper] shows a pattern of higher rainfall in the north than south, west than east, and mountains than basins. Stations with $ $40.0 mm are located in the eastern and southern Tarim Basin, while stations with 40.1–100.0 mm are found on the southern slope of the West Tianshan Mountains. Stations exceeding 100.0 mm are concentrated in the middle mountain belt at 1500–2500 m altitude (except Wushi at 1396.8 m), including Wuqia, Aheqi, Wushi, Bayinbuluke, and Taxkorgan. The Turgart station above 3000 m has lower annual rainfall (60.0 mm) due to high-altitude low temperatures favoring snowfall over rainfall, though Taxkorgan also exceeds 200 mm.

All stations show increasing annual rainfall trends. Classified by increasing rate: 4 stations (9%) show 0.0–1.0 mm $\cdot$ $(10a)^{-1}$ increases (eastern Bazhou desert); 17 stations (38%) show 1.1–6.0 mm $\cdot$ $(10a)^{-1}$ increases (southern Tianshan and northern Kunlun slopes); 15 stations (33%) show 6.1–12.0 mm $\cdot$ $(10a)^{-1}$ increases (southern Tianshan slopes); and 9 stations (20%) show 12.1–24.0 mm $\cdot$ $(10a)^{-1}$ increases (Wuqia, Aheqi, Wushi, Bayinbuluke), all located in the 1500–2500 m middle mountain belt and coinciding with highest rainfall stations.

These findings indicate consistency between rainfall amount and increasing rate —stations with higher rainfall show greater increases, primarily in the middle mountain belt, which contributes most to southern Xinjiang' s wettening trend.

2.2.1 Extreme Rainfall Thresholds in Southern Xinjiang To determine extreme rainfall thresholds, the 95th, 97th, 99th, and 99.9th percentiles were compared . Using the 95th percentile yields thresholds of 5.4–11.7 mm, corresponding to 312–620 rainfall days—too frequent for extreme events. The 97th percentile gives 10.8–18.7 mm thresholds, while the 99th percentile yields 14.1–35.4 mm thresholds, mostly corresponding to the >12.0 mm heavy rain level with 62–155 days. The 99.9th percentile produces 25.7–45.4 mm thresholds, corresponding to only 6–15 days. The 99th percentile provides the most appropriate threshold, balancing rarity and representativeness.

The 99th percentile threshold ranges from 14.1–35.4 mm across stations, averaging 30.8 mm. Higher thresholds (30.1–36.0 mm) occur in the Pamir Plateau and western mountainous areas, while lower thresholds (14.1–18.0 mm) appear in the Taklamakan Desert region. Thresholds show an increasing trend at 0.7 mm $\cdot$ $(10a)^{-1}$, having increased by approximately 4.3 mm over the study period. The fastest increases [>2.0 mm $\cdot$ $(10a)^{-1}$] occur at 7 stations (16%) in Kashgar, western Hotan, and northern Bazhou mountainous areas.

2.2.2 Spatial and Temporal Distribution of Extreme Rainfall Thresholds Based on the 99th percentile thresholds, spatial analysis [Figure 6: see original paper] reveals that 18 stations (40%) have thresholds of 18.1–24.0 mm, mainly in the Taklamakan Desert margin; 16 stations (36%) have thresholds of 24.1–30.0 mm, primarily on the southern Tianshan slopes; and 11 stations (24%) have thresholds of 30.1–36.0 mm, mostly on the western Tianshan southern slope and eastern Pamir Plateau.

Threshold change rates show: 4 stations (9%) with -0.1 to 1.0 mm $\cdot$ $(10a)^{-1}$, located in the eastern basin desert; 17 stations (38%) with 1.1–2.0 mm $\cdot$ $(10a)^{-1}$, mainly on the Kunlun northern slope; 15 stations (33%) with >2.0 mm $\cdot$ $(10a)^{-1}$, concentrated in the middle and western Tianshan mountains; and only Pishan station with a decreasing rate of -2.0 mm $\cdot$ $(10a)^{-1}$.

These patterns indicate that higher extreme rainfall thresholds occur in the Pamir Plateau and Kunlun Mountain areas, with most stations showing increasing thresholds, particularly pronounced in central-western Hotan, northern Aksu, and northern Bazhou mountainous regions.

2.2.3 Spatial and Temporal Distribution of Extreme Rainfall Events Using the 99th percentile thresholds, extreme rainfall events were identified when daily rainfall exceeded station-specific thresholds. Southern Xinjiang experienced 10–20 extreme events at most stations, with Tianshan Mountain stations exceeding 20 events. Spatially [Figure 7: see original paper], 18 stations (40%) recorded 11–16 events, mainly on Tianshan and Pamir slopes; 17 stations (38%) recorded 17–20 events, primarily on the Kunlun northern slope and in the central Taklamakan Desert; and only 10 stations (22%) recorded >20 events (Bayinbuluke, Keping, Wushi, Baluntai, Baicheng, Wuqia, and Aheqi), concentrated on the southern Tianshan middle-lower slopes.

Temporally, extreme rainfall events totaled 1,881 occurrences across all stations, with 23 years (37%) exceeding the average of 30.3 events per year. The overall trend shows a significant increase at 0.9 events·$(10a)^{-1}$, indicating more frequent extreme rainfall events in southern Xinjiang.

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3. Conclusions

(1) From 1961 to 2022, all meteorological stations in southern Xinjiang showed increasing annual rainfall trends, with greater increases in the west than east and mountains than basins. Stations with higher annual rainfall showed more pronounced increases, with the maximum increase region located in the middle mountain belt at 1500–2500 m altitude.

(2) Using percentile analysis of 45 meteorological stations, the 99th percentile was determined as the extreme rainfall threshold for southern Xinjiang. Thresholds ranged from 18.1–30.0 mm, with higher values in western mountainous and piedmont regions than in eastern basin-desert areas. Extreme rainfall thresholds increased at 0.7 mm $\cdot$ $(10a)^{-1}$, with 43 stations showing increases and only 2 decreasing. The fastest increases occurred in Kashgar, western Hotan, and northern Bazhou mountainous areas.

(3) Extreme rainfall events in southern Xinjiang occurred 10–20 times at most stations, with Tianshan Mountain stations experiencing >20 events (maximum 29 events at Aheqi). Events increased significantly at 0.9 events $\cdot$ $(10a)^{-1}$.

(4) Southern Xinjiang' s wettening trend is primarily driven by increases in large-scale rainfall events. While micro-rain days and contributions decreased, heavy rainstorm and extreme rainstorm events increased significantly in both frequency and amount.

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