Spatiotemporal Variations of Warm-Season Heavy Precipitation with Different Durations in Shaanxi Province, 1981–2020 (Postprint)

Authors: Cai Xinling, Cai Yixuan, Ye Dianxiu, Li Qian, Hu Yuantao, Hu Lin

Date: 2025-02-27T00:00:00+00:00

Abstract

Using hourly precipitation data from 95 national meteorological observation stations in Shaanxi Province during the warm season (May–September) from 1981 to 2020, combined with various statistical methods, the spatiotemporal variations of heavy precipitation for four durations (1 h, 3 h, 6 h, 12 h) were analyzed. The results show that: (1) Short-duration heavy precipitation in Shaanxi Province is mainly concentrated in July–August, with high-incidence areas for all four durations located in the Qinba Mountains of southern Shaanxi, and low-incidence areas located in the central Guanzhong Plain and along the Great Wall in northern Shaanxi. (2) The spatial differences in precipitation extremes for each duration are relatively large, with shorter durations exhibiting stronger local characteristics in extreme value distribution. (3) Over the past 40 years, heavy precipitation of all durations in Shaanxi Province has shown an increasing and intensifying trend, particularly significant for 3-hour heavy precipitation. (4) The trend changes of heavy precipitation for each duration exhibit spatial non-uniformity, with increasing trends observed along the Yellow River in northern Shaanxi and in the central-southern parts of southern Shaanxi, while decreasing trends are found in the southern part of northern Shaanxi and the central Guanzhong Plain; moreover, the shorter the duration, the larger the area exhibiting an increasing trend in heavy precipitation. (5) The diurnal variation of heavy precipitation differs between north and south, with shorter durations showing more pronounced diurnal variations, particularly notable for short-duration heavy precipitation in northern Shaanxi, which tends to occur in the evening or nighttime, posing greater hazards.

Full Text

Spatial and Temporal Variation Characteristics of Heavy Precipitation with Different Durations During the Warm Season in Shaanxi Province from 1981 to 2020

CAI Xinling[1], CAI Yixuan[2], YE Dianxiu[3], LI Qian[1], HU Yuantao[1], HU Lin[1]

[1]Shaanxi Provincial Climate Center, Xi' an 710014, Shaanxi, China

[2]Zhouzhi County Emergency Management Bureau, Xi' an 710400, Shaanxi, China

[3]National Climate Center, Beijing 100081, China

Abstract

This study analyzes the spatiotemporal variations of heavy precipitation across four durations (1 h, 3 h, 6 h, and 12 h) during the warm season (May–September) in Shaanxi Province from 1981 to 2020, using hourly precipitation data from 95 national meteorological observation stations and various statistical methods. The results reveal that: (1) Heavy precipitation events across all durations are concentrated in July and August. High-frequency zones for all four durations are located in the Qinling-Daba mountainous region of southern Shaanxi, while low-frequency zones occur in the central Guanzhong Plain and along the Great Wall in northern Shaanxi. (2) Spatial differences in precipitation extremes are substantial for each duration, with shorter durations exhibiting stronger local characteristics in extreme value distribution. (3) Over the past 40 years, both intensity and frequency of heavy precipitation across all durations have shown increasing trends, with the 3 h duration showing the most significant increase. (4) Spatial trends in heavy precipitation are non-uniform: increasing trends are observed along the Yellow River in northern Shaanxi and in south-central Shaanxi, while decreasing trends appear in southern northern Shaanxi and central Guanzhong Plain. Notably, shorter durations exhibit increasing trends over larger areas. (5) Diurnal variations in heavy precipitation differ between northern and southern Shaanxi, with shorter durations showing more pronounced diurnal cycles. The diurnal variation is most prominent for short-duration heavy precipitation in northern Shaanxi, where peak occurrence in the evening or nighttime poses greater disaster risks.

Keywords: short-duration heavy precipitation; change trend; spatial and temporal distribution; Shaanxi Province

Introduction

Numerous studies indicate that extreme heavy precipitation events are becoming more frequent and intense against the backdrop of climate warming, with resulting disaster losses and impacts becoming increasingly severe [1-3]. For example, a short-duration heavy precipitation event on August 8, 2010 in Zhouqu

County, Gansu Province triggered catastrophic debris flows, while torrential rains on July 21, 2012 in Beijing and July 20, 2021 in Zhengzhou caused severe flooding disasters [4-6]. The IPCC AR6 report notes that as global warming intensifies, heavy precipitation events are likely to become stronger and more frequent [7], with a tendency to occur over shorter time scales [8]. Compared with general heavy rain (daily precipitation $ $50 mm), short-duration heavy precipitation (hourly precipitation $ $20 mm) is characterized by higher precipitation efficiency, greater disaster potential, and greater forecasting difficulty [9-11].

Short-duration heavy precipitation is primarily caused by mesoscale convective systems, exhibits strong locality, and is significantly influenced by terrain. Wang et al. [5] used dense automatic station hourly precipitation data from Henan Province during 2011–2017 and found that terrain significantly amplifies precipitation, mainly by increasing the frequency of short-duration heavy precipitation events. Ran et al. [12] analyzed hourly precipitation data from dense automatic stations in the Sichuan Basin during 2008–2020, revealing that short-duration heavy precipitation is concentrated in the transition zone between the southwestern high mountains and the basin, as well as along the northwestern Longmen Mountains. Both frequency and precipitation amount show increasing trends, which are highly correlated with the number of geological disasters in the northwestern basin. Terrain not only affects the spatial distribution of heavy precipitation but also influences its diurnal variation. Under the influence of the large-scale Tibetan Plateau topography, Sichuan Province exhibits a significant "night rain" characteristic during the warm season, with nighttime heavy precipitation events showing more pronounced features [13]. The Qinling Mountains and surrounding areas demonstrate distinct north-south differences in diurnal precipitation patterns during the warm season, with afternoon rainfall on the Loess Plateau occurring mostly north of the Qinling [14]. Different short-duration heavy precipitation events may be caused by weather systems on different time scales, and their spatiotemporal distributions also show distinct characteristics. Guo et al. [15] found that the increasing trend of 1 h heavy precipitation frequency in Hunan Province was more significant than that of 3 h events. In eastern Northwest China, the interannual variation of short-duration heavy precipitation is small, but regional short-duration heavy precipitation processes show a clear increasing trend [16]. Miao et al. [17] used hourly precipitation data from 2005–2017 and found that annual variation amplitude of short-duration heavy precipitation station frequency in Shanxi Province was large, with increasing trends showing higher growth rates in the south than in the north, and significantly higher rates in mountainous areas than in basins.

Shaanxi Province is located in the inland 腹地 of China, spanning from the Loess Plateau in northern Shaanxi to the Guanzhong Plain and then to the Qinling-Daba Mountains in southern Shaanxi. Under these unique geographical locations, topographic features, and climatic conditions, questions remain regarding the distribution of short-duration heavy precipitation across the province, the corresponding differences in heavy precipitation frequency and intensity, and the diurnal variations of heavy precipitation across different durations. These issues require systematic and in-depth analysis. Current research on short-duration heavy precipitation in Shaanxi mainly focuses on synoptic perspectives such as circulation characteristics, moisture and energy conditions, and convective triggering mechanisms [19-22], providing insights for forecasting and early warning. However, climatological studies on the spatiotemporal distribution and diurnal variation of short-duration heavy precipitation are still limited [23], particularly regarding extreme values, frequency, and their variations across different short durations. Therefore, this paper uses hourly precipitation data from 1981–2020 to conduct statistical analysis of heavy precipitation events across different durations, aiming to understand their spatiotemporal variation characteristics and disaster-causing features, thereby providing scientific support for heavy precipitation prediction, early warning, and meteorological disaster prevention in Shaanxi Province.

1. Data and Methods

1.1 Study Area Overview

Shaanxi Province is situated in the inland 腹地 of China, with a narrow north-south extent. The Qinling Mountains traverse its central region, with the Loess Plateau to the north, the Qinling-Daba mountainous area to the south, and the Guanzhong Plain in the middle, covering a total area of 205,624.3 km^2. The province is interlaced with the Wei, Han, and Jialing Rivers. Climatically, it spans the mid-temperate, warm-temperate, and north-subtropical zones, lying on the margin of monsoon influence. Precipitation shows large interannual variability and uneven spatiotemporal distribution within the year, with frequent flood and drought disasters. The topographic elevation and distribution of meteorological stations in the study area are shown in Figure 1 [Figure 1: see original paper].

1.2 Data Sources

The precipitation data used in this study consist of hourly precipitation records from 95 national-level surface meteorological stations in Shaanxi Province (27 in northern Shaanxi, 32 in the Guanzhong region, and 36 in southern Shaanxi) during the warm season (May–September) from 1981 to 2020. The dataset was obtained from the China National Meteorological Information Center’ s hourly precipitation dataset for national surface meteorological stations (V3.0). Before use, the precipitation data underwent consistency checks for boundary values, temporal consistency, and spatial consistency. Additionally, to ensure the data were not affected by outliers, manual daily precipitation observations were used to verify the hourly precipitation data.

1.3 Definition and Statistical Methods

Based on operational regulations from the China Meteorological Administration, combined with the climatic characteristics of Shaanxi and relevant literature [15-17], this study employs a fixed threshold method to define heavy precipitation events across four durations. A heavy precipitation event is defined when: 1 h precipitation $ $20 mm; 3 h precipitation $ $30 mm; 6 h precipitation $ $50 mm; or 12 h precipitation $ $50 mm. The 1 h precipitation amount represents the actual observed rainfall, while the 3 h, 6 h, and 12 h precipitation amounts are cumulative values over the preceding 3 h, 6 h, and 12 h periods, respectively.

For frequency statistics, if a station' s precipitation for a given duration exceeds the threshold, it is counted as one heavy precipitation event. If the interval between two consecutive events is less than the duration length, they are counted as a single event, and so on. For example, if precipitation at 20:00, 21:00, 22:00, and 23:00 all exceed 30 mm, the period from 20:00 to 23:00 is counted as one 3 h heavy precipitation event. That is, four consecutive time steps meeting the 3 h threshold are counted as only one event for that duration, with no overlap between events (e.g., between 20:00 and 23:00).

Within a specific time period, the sum of heavy precipitation events across all stations is used as the regional heavy precipitation frequency index. Monthly variations are analyzed using the percentage of monthly heavy precipitation events relative to the total frequency. Linear trend estimation [18] is applied to analyze long-term trends in heavy precipitation indices.

2. Results

2.1 Spatial Distribution of Extreme Precipitation Values

Figure 2 [Figure 2: see original paper] shows the spatial distribution of precipitation extremes for different durations during May–September from 1981 to 2020. Overall, the maximum precipitation values for all four durations are relatively low along the Great Wall in northern Shaanxi, while high-extreme-value zones are scattered. Spatial differences in 1 h precipitation extremes across Shaanxi are substantial, ranging from 34.2 mm at Dingbian station to 124.5 mm at Taibai station. Most areas have hourly rainfall extremes of 50–70 mm, while stations with values $ $100 mm are scattered mainly in the Qinling-Daba mountainous region of southern Shaanxi, central Guanzhong Plain, western Weibei region, and central-southern northern Shaanxi (Figure 2a).

The 3 h precipitation extremes range from 53.8 mm at Dingbian station to 151.7 mm at Zhenba station, with most areas experiencing 90–130 mm. Stations with values $ $130 mm are distributed linearly from Zhenba County in the far south to Jiaxian County in northern Shaanxi, and east-west along the Wei River mainstream (Figure 2b). The 6 h precipitation extremes range from 67.3 mm at Zichang station to 187.7 mm at Huayin station, with most areas receiving 100–160 mm. High-value stations are scattered across western Guanzhong, western southern Shaanxi, and northeastern northern Shaanxi (Figure 2c). The 12 h precipitation extremes range from 73.0 mm at Sanyuan station to 217.2 mm at Jiaxian station, with most areas receiving 70–100 mm (Figure 2d).

These results demonstrate that spatial differences in heavy precipitation extremes across different durations in Shaanxi are considerable, with shorter durations showing stronger local characteristics in extreme value distribution. High-extreme-value zones exist in three regions: southern Shaanxi, central Guanzhong, and central-northern northern Shaanxi. This pattern primarily results from the influence of the southwest monsoon, the advance and retreat of the western Pacific subtropical high, and the eastward movement of plateau vortices, combined with topographic wave effects from the Qinling Mountains and Loess Plateau that lead to large short-duration heavy precipitation extremes. In contrast, short-duration heavy precipitation is relatively less frequent in the Guanzhong Plain (Figure 2). Notably, precipitation extremes for different durations are relatively large in central-eastern northern Shaanxi, indicating strong warm-season precipitation intensity, pronounced locality, and the need for vigilance against sudden heavy precipitation in this region.

2.2 Spatial Distribution of Heavy Precipitation Frequency

The spatial distribution of heavy precipitation frequency for different durations during May–September from 1981 to 2020 is shown in Figure 3 [Figure 3: see original paper]. Frequency is low in the sandy area of northwestern northern Shaanxi and central-western Guanzhong Plain, with the lowest values (only 5–10 events) at Baoji, Xingping, and Dingbian stations. In contrast, frequencies exceed 50 events in the Qinling-Daba mountainous region of southern Shaanxi, reaching a maximum of 65 events at Shangnan station. The spatial distribution patterns are similar across the four durations, all showing characteristics of more events in the south and east, fewer in the north and west. Due to the natural barrier of the Qinling Mountains blocking the northward movement of warm, moist air from the south, precipitation north of the Qinling is significantly less than in the south. Influenced by unique geographical location and topographic uplift factors, heavy precipitation frequency shows substantial north-south differences across Shaanxi [24], with pronounced locality in short-duration heavy precipitation occurrence. High-frequency zones are clearly concentrated in the Qinling-Daba mountainous region of southern Shaanxi, including Shangnan County in Shangluo City; Ziyang, Shiquan, Zhenping, and Ningshan counties in Ankang City; and Zhenba, Ningqiang, and Foping counties in Hanzhong City.

2.3 Temporal Variations

2.3.1 Monthly Variations Monthly variations in heavy precipitation frequency are analyzed using the percentage of events in each month relative to the total number of events during 1981–2020 in Shaanxi Province. Events with 1 h precipitation $ $20 mm occur most frequently, with an annual average of 5,840–5,880 station-events, followed by $ $30 mm/3h events with 2,056 station-events. As shown in Figure 4 [Figure 4: see original paper], heavy precipitation across all durations is concentrated in July and August, accounting for 71%-87% of the total frequency during the flood season (May-September). September ranks second, while May accounts for less than 5% and June has the lowest proportion. This pattern aligns with Niu et al. [25], who found that North China regional rainstorm frequency peaks in July and August, accounting for 70%-85% of the flood season total, with June having the lowest proportion. The consistency between these findings suggests that temporal distribution characteristics are similar for North China rainstorms and short-duration heavy precipitation, likely because both are dominated by convective and mixed-type precipitation during July-August, which tends to be more persistent.

2.3.2 Diurnal Variations Spanning north-subtropical, warm-temperate, and temperate climate zones, Shaanxi exhibits significant north-south differences in precipitation diurnal variation. Regional analysis of diurnal variations in heavy precipitation across different durations reveals that 1 h heavy precipitation shows the most pronounced diurnal cycle, while 12 h heavy precipitation shows the smallest (Figure 5 [Figure 5: see original paper]). The 1 h heavy precipitation peaks in the afternoon to early evening across all regions, with northern Shaanxi showing the most significant diurnal variation as a single peak at 17:00-18:00. Guanzhong and southern Shaanxi show double-peak patterns, with primary peaks at 17:00-21:00 and secondary peaks at 07:00-08:00. The frequent occurrence of 1 h heavy precipitation in the afternoon is mainly due to strong convection [26].

The 3 h heavy precipitation shows pronounced diurnal variation in northern and southern Shaanxi as a double-peak pattern (Figure 5b), with the primary peak in northern Shaanxi at 17:00-18:00 and a secondary peak at 05:00-06:00; in southern Shaanxi, the primary peak occurs at 05:00-06:00 and the secondary peak at 19:00-21:00. The 6 h heavy precipitation diurnal variation is relatively flat, with only a midday trough (Figure 5c). The 12 h heavy precipitation diurnal variation shows a single-peak distribution, with significantly more events at night than during the day (Figure 5d), indicating that most heavy precipitation occurs during nighttime hours across Shaanxi, increasing the difficulty of disaster prevention and mitigation.

2.4 Trend Analysis

2.4.1 Trends in Extreme Values The maximum values from annual extremes of different-duration heavy precipitation across Shaanxi are selected as provincial extremes. The 1 h heavy precipitation extreme shows large interannual fluctuations with no significant trend over the past 40 years, but exhibits stage-wise characteristics with larger extremes from the mid-1990s to early 2010s (Figure 6a [Figure 6: see original paper]). The 3 h heavy precipitation extreme shows a significant increasing trend through fluctuations, with a rate of 5.8 $mm \cdot (10a)^{-1}$ that passes the 0.01 significance test (Figure 6b). The 6 h and 12 h heavy precipitation extremes also show increasing trends at rates of 4.2 mm · $(10a)^{-1}$ and 3.8 mm · $(10a)^{-1}$, respectively, both passing significance tests (Figure 6c, 6d). Overall, heavy precipitation extremes across different durations in Shaanxi show large interannual variation and increasing trends, with the most significant enhancement for the 3 h duration.

Spatial patterns of trends in heavy precipitation extremes across different durations (figure omitted) show non-uniform characteristics. Most stations show increasing trends, with more stations showing increases for shorter durations. The increasing zones are mainly distributed in Yulin, Xianyang, Weinan, Shangluo, and Ankang cities, with significantly increasing areas showing rates above 5.8 mm · $(10a)^{-1}$. Decreasing trends are mainly found in southern Yan' an, central Guanzhong Plain, and western southern Shaanxi.

2.4.2 Trends in Frequency Heavy precipitation station-events across all durations during the warm season in Shaanxi show increasing trends. The 3 h heavy precipitation shows the largest increase at 4.2 station-events · $(10a)^{-1}$, followed by 6 h (3.8 station-events · $(10a)^{-1}$) and 1 h (3.2 station-events · $(10a)^{-1}$), all passing the 0.05 significance test. The 12 h heavy precipitation also shows an increase but without statistical significance. Monthly analysis reveals decreasing trends for all durations in June (not significant), while July and August show significant increasing trends for all durations, particularly for 1 h and 3 h events. September shows slight decreases for 1 h events but increases for other durations.

Figure 7 [Figure 7: see original paper] shows annual variations in heavy precipitation frequency across different durations. The spatial distribution of annual frequency trends (Figure 8 [Figure 8: see original paper]) reveals non-uniform patterns across Shaanxi. Most stations show increasing trends, with more stations showing increases for shorter durations. Increasing zones for 1 h heavy precipitation are mainly in Yulin, Xianyang, Weinan, Shangluo, and Ankang, with significantly increasing areas showing rates above 3.2 station-events · $(10a)^{-1}$. Decreasing trends appear in southern Yan' an, central-eastern Guanzhong, and western southern Shaanxi. The 3 h heavy precipitation increasing zones are mainly in northern Shaanxi and central-eastern southern Shaanxi, with significantly increasing areas above 4.2 station-events · $(10a)^{-1}$. Decreasing trends are found in southern northern Shaanxi and most of Guanzhong, with western southern Shaanxi also showing decreases. Overall, areas along the Yellow River in northern Shaanxi and in south-central southern Shaanxi show increasing trends across all durations, while southern northern Shaanxi and central Guanzhong Plain show decreasing trends. The spatial patterns are relatively consistent across durations.

3. Discussion

Heavy precipitation can easily trigger severe disasters including flash floods, debris flows, and urban waterlogging. As global warming intensifies, heavy precipitation events tend to occur over shorter time scales [3]. This study categorizes heavy precipitation events within 12 h by duration to analyze spatiotemporal variations across different short durations. Overall, short-duration heavy precipitation in Shaanxi shows a pattern of less in the north and more in the south, consistent with the general distribution of rainstorms in the province and with the geographic distribution of short-duration heavy precipitation frequency across China reported by Chen et al. [1]. Influenced by latitude, terrain, and moisture transport, high-frequency zones for all durations are concentrated in the Qinling-Daba Mountains, while the central Guanzhong Plain and the region along the Great Wall in northern Shaanxi are low-frequency zones.

Clarifying the spatiotemporal differences among different short-duration heavy precipitation events can provide references for forecasting, early warning, and developing detailed disaster prevention measures. Shi et al. [27] found that the probability of extreme precipitation with low probability but high hazard is increasing in most areas of Shaanxi, with comprehensive extreme precipitation hazard showing a south-high to north-low distribution from southern to northern Shaanxi. However, it is noteworthy that some areas in northern Shaanxi with low heavy precipitation frequency experience very high precipitation intensity, with hourly intensity exceeding 50 $mm \cdot h^{-1}$ and hosting provincial extremes for different short durations. This indicates that short-duration precipitation intensity in northern Shaanxi during the warm season is greater than in southern Shaanxi, and with large interannual variation in extreme heavy precipitation, such events can be easily overlooked. Therefore, while preventing extreme precipitation with high comprehensive hazard in the Qinling-Daba Mountains, attention must also be paid to potential floods or landslides and debris flows caused by local short-duration heavy precipitation in northern Shaanxi. Additionally, as heavy precipitation tends to occur at night, increasing the difficulty of disaster response, nighttime disaster prevention awareness should be strengthened. This study did not fully consider the complex terrain effects of the Qinling Mountains and Loess Plateau on short-duration heavy precipitation. Future work will incorporate dense regional (township-level) automatic station data and multi-source fused high-precision grid observations to conduct refined analysis of extreme heavy precipitation and disaster-critical thresholds for these complex terrain areas, providing scientific support for regional defense against heavy precipitation-induced waterlogging and flooding.

4. Conclusions

Based on hourly precipitation data from 95 national meteorological stations in Shaanxi Province during 1981–2020, this study analyzes spatiotemporal variation characteristics of heavy precipitation across different durations. The main conclusions are:

(1) Spatial differences in heavy precipitation extremes across different durations in Shaanxi are substantial, ranging from 34.2–124.5 mm for 1 h, 53.8–151.7 mm for 3 h, 67.3–187.7 mm for 6 h, and 73.0–217.2 mm for 12 h. High-extreme-value zones are scattered across southern Shaanxi, central

Guanzhong, and the region along the Yellow River in northern Shaanxi. Shorter durations exhibit stronger local characteristics in extreme value distribution.

(2) Spatial differentiation in heavy precipitation frequency is evident across Shaanxi, showing a pattern of more in the south and east, less in the north and west. High-frequency zones are concentrated in the Qinling-Daba Mountains, while the central Guanzhong Plain and the region along the Great Wall in northern Shaanxi are low-frequency zones.

(3) Heavy precipitation across different durations in Shaanxi is concentrated in July and August, accounting for 70%–85% of the flood season (May–September) total. Diurnal variations show regional differences between northern and southern Shaanxi, with shorter durations exhibiting more pronounced diurnal cycles. The diurnal variation is most prominent for short-duration heavy precipitation in northern Shaanxi, with peaks in the evening or late night.

(4) Overall, heavy precipitation across all durations in Shaanxi has shown increasing trends over the past 40 years, with the most significant increase for the 3 h duration. Spatial trends are non-uniform, with increasing trends in northern Shaanxi along the Yellow River and in south-central southern Shaanxi, and decreasing trends in southern northern Shaanxi and central Guanzhong Plain. Shorter durations show increasing trends over larger areas.

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