Spatiotemporal Characteristics of Short-Duration Heavy Precipitation in Western Guanzhong, Shaanxi, and Its Relationship with Topography

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Abstract

Investigating the spatiotemporal characteristics of short-duration heavy rainfall and its mechanisms of association with topography is of scientific significance for constructing regionally refined short-term nowcasting models and improving the risk assessment and defense capabilities for extreme precipitation disasters. Using hourly precipitation data from 327 meteorological stations in western Guanzhong, Shaanxi, during the warm seasons (April–September) of 2018—2024, ERA5 reanalysis data, and 30 m elevation data, this study analyzes the spatiotemporal distribution characteristics of short-duration heavy rainfall in western Guanzhong through methods including IDW (inverse distance spatial interpolation), principal component analysis, and linear regression, and explores the influence of topography on the distribution of short-duration heavy rainfall. The results show that: (1) During the warm seasons of 2018—2024, short-duration heavy rainfall in western Guanzhong showed an increasing trend, with rainfall intensity mainly ranging from 20~40 mm · h-1, concentrated primarily from mid-July to early August, and the maximum rainfall intensity exceeding 50 mm · h-1. The diurnal variation exhibited a bimodal pattern, with 18:00—23:00 being the most active period. (2) The spatial distribution was uneven, with high-frequency areas located on the high-altitude loess tablelands in the north and the northern foothills of the western Qinling Mountains, and low-frequency areas located in the low-altitude plains in the east. Day–night distribution differences were pronounced: high-frequency areas during the day were scattered and mostly appeared north of the Weihe River, while at night they were concentrated on the northern loess tablelands. (3) The frequency of short-duration heavy rainfall was significantly affected by altitude, latitude, and longitude, with altitude playing the most prominent role, followed by topographic thermal uplift, while dynamic uplift had the weakest influence. The variation of short-duration heavy rainfall with altitude exhibited a "single-peak" pattern, occurring mainly at elevations of 400~1300 m; above 1300 m, the frequency of short-duration heavy rainfall decreased with increasing elevation. The results provide a theoretical basis for local forecasting and early warning of short-duration heavy rainfall.

Full Text

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Spatiotemporal Characteristics of Short-Duration Heavy Precipitation in Western Guanzhong, Shaanxi, and Its Relationship with Topography

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Abstract: Studying the spatiotemporal characteristics of short-duration heavy precipitation and its linkage mechanism with topography is of scientific significance for building regionally refined short-term nowcasting models and improving the capacity for risk assessment and prevention of extreme precipitation disasters. Using hourly precipitation observations from 327 meteorological stations in the warm seasons (April–September) of 2018–2024 in western Guanzhong, Shaanxi, together with ERA5 reanalysis data and 30 m elevation data, this study analyzed the spatiotemporal distribution characteristics of short-duration heavy precipitation in western Guanzhong by means of IDW (inverse-distance spatial interpolation), principal component analysis, linear regression, and other methods, and explored the influence of topography on the distribution of short-duration heavy precipitation. The results show that: (1) During 2018–2024, short-duration heavy precipitation in the warm season in western Guanzhong showed an increasing trend in occurrence. Rain intensity was mainly $20 \sim 40\ \mathrm{mm \cdot h^{-1}}$, concentrated chiefly from mid-July to early August, with maximum rain intensity exceeding $50\ \mathrm{mm \cdot h^{-1}}$. Its diurnal variation was bimodal, and 18:00–23:00 was the most active period. (2) The spatial distribution was uneven. High-frequency areas were located on the northern high-elevation loess tablelands and the northern foot of the western Qinling Mountains, while low-frequency areas were located in the eastern low-elevation plain. Day–night differences in distribution were obvious: high-frequency areas during the daytime were scattered and mostly appeared north of the Weihe River, whereas at night they were concentrated on the northern loess tablelands. (3) The number of short-duration heavy-precipitation events was significantly affected by elevation, latitude, and longitude; among these, elevation had the most prominent effect, followed by topographic thermal uplift, while dynamic uplift had the weakest effect. The number of short-duration heavy-precipitation events changed with elevation in a unimodal pattern, occurring mainly at elevations of 400–1300 m; above 1300 m, the number of events decreased with increasing elevation. The results provide a theoretical basis for local forecasting and warning of short-duration heavy precipitation.

Keywords: western Guanzhong; short-duration heavy precipitation; hourly scale; spatiotemporal characteristics; topography

Short-duration heavy precipitation refers to severe convective weather in which precipitation within a short period exceeds a specified threshold, generally defined as 1 h precipitation ≥ 20 mm. Because it has the characteristics of a short life cycle, strong suddenness, large hourly rainfall intensity, and pronounced locality, it has become a key focus and difficulty in operational weather forecasting and warning. Against the background of global climate warming, short-duration heavy-precipitation processes in Northwest China have increased markedly[1], and precipitation has increased significantly[2]. When precipitation intensity is strong or the duration is long, it may cause urban waterlogging and even trigger secondary disasters such as landslides, debris flows, and mountain torrents. Many scholars have analyzed short-duration heavy precipitation in terms of climatic characteristics[3–5], influencing systems[6–7], formation mechanisms[8–9], environmental physical quantities[10–11], radar characteristics[12–14], and other aspects. These results provide reference bases for the forecasting and warning of short-duration heavy precipitation. Under the influence of climate and topography, the characteristics of heavy precipitation and the diurnal variation of precipitation in different regions show obvious regionality[15].

Topography has a significant influence on heavy precipitation. Through its dynamic and thermal effects, topography can alter the motion trajectories of atmospheric circulation and the thermal state of the atmosphere, thereby affecting the distribution and intensity of precipitation[16–19]. At present, methods for evaluating the influence of topography on precipitation mainly focus on two aspects: statistically analyzing the correlation between topographic factors and precipitation[5,20–21], and using hydrodynamic equations and related atmospheric equations to simulate precipitation in mountainous areas[22–23]. The terrain of Shaanxi is higher in the north and lower in the south, and the Qinling Mountains traverse the central part, forming the natural geographical boundary between Guanzhong and southern Shaanxi. Many studies have addressed the influence of Qinling topography on severe convection or rainstorms in the Guanzhong region. At the northern foot of the Qinling Mountains, under the combined action of local thermal circulation and the isallobaric gradient, an ultra-low-level strong westerly belt is readily formed; together with the windward slope, it produces horizontal convergence, increasing cyclonic vorticity and enhancing precipitation on the windward slope[24–25]. Meanwhile, topographic convergence lines or mesoscale cyclonic circulations generated at the northern foot of the Qinling Mountains can, through thermal effects, initiate new convective systems and cause short-duration heavy precipitation[26–27]. In addition, when a cold front advances southward and is blocked by the Qinling Mountains, a jet forms within the boundary layer at the northern foot; strong thunderstorm cells are continuously generated along the jet and move eastward, forming a distinct training effect and causing large-scale occurrences in the mountainous area

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heavy-precipitation weather [9].

The western Guanzhong region is located north of the Qinling Mountains. In summer, short-duration heavy precipitation and other severe convective weather occur frequently, yet relatively few studies have examined the spatiotemporal distribution characteristics and evolution patterns of local short-duration heavy precipitation. Meanwhile, the specific mechanisms by which mesoscale and microscale terrain in the Guanzhong region affects precipitation remain not fully clear. In operational weather forecasting, however, fully considering the influence of terrain on the distribution of heavy precipitation is crucial for improving the accuracy of refined forecasts. Therefore, based on hourly precipitation data from 327 meteorological stations in western Guanzhong during 2008–2024, this study analyzes the spatiotemporal distribution characteristics of short-duration heavy precipitation. In combination with a DEM digital elevation model, and by comprehensively applying methods such as principal component analysis and linear regression, it examines the statistical relationship between short-duration heavy precipitation and geographic terrain factors, and evaluates the mechanism of short-duration heavy precipitation under the influence of terrain, aiming to provide a theoretical reference for optimizing local short-duration heavy-precipitation forecasting and early-warning services.

1 Data and Methods

1.1 Overview of the Study Area

The western Guanzhong region in this study refers to the western section of the Guanzhong Plain in Shaanxi Province. Based on the movement paths of weather systems and their sequences of influence, and in combination with the needs of regional division for weather forecasting, the study area is defined as Baoji City, Xianyang City, and Yangling District, so as to ensure the integrity of administrative divisions (Fig. 1). The region borders the Weibei Loess Plateau to the north and adjoins the Qinling Mountains to the south; the Longshan Mountains lie to the west, and mountains, rivers, and tablelands coexist. It has a warm-temperate semi-humid monsoon climate, with four distinct seasons and concurrent rain and heat. In summer, local and sudden short-duration heavy precipitation occurs frequently and is highly likely to induce local geological disasters such as mountain torrents, landslides, and debris flows. For example, during the night of July 28, 2023, short-duration heavy precipitation occurred in parts of Linyou County and Binzhou City in western Guanzhong. The precipitation was intense and lasted for a long time, triggering severe flood disasters in seven townships of Binzhou City, Xianyang City, and causing direct economic losses of 5.91×10^7 yuan.

1.2 Research Data

The precipitation data comprise hourly precipitation observations in the warm seasons (April–September) of 2018–2024 from 24 national automatic meteorological stations and 303 regional meteorological stations in western Guanzhong (Baoji City, Xianyang City, and Yangling District). The data were obtained from the Shaanxi Meteorological Information Center. The upper-air wind field uses the fifth-generation global atmospheric reanalysis data (ERA5) from the European Centre for Medium-Range Weather Forecasts, with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ and a temporal resolution of 1 h. Digital elevation model (DEM) data were obtained from the Geospatial Data Cloud (https://www.gscloud.cn), with a spatial resolution of 30 m $\times$ 30 m. ArcGIS software was used to spatially resample the DEM data and extract the elevation, slope, and aspect of each meteorological station.

1.3 Case Selection

In this paper, the sum of the number of occurrences of short-duration heavy precipitation at all stations is recorded as the number of short-duration heavy-precipitation occurrences; the cumulative number of short-duration heavy-precipitation events at a single station is recorded as the single-station number of short-duration heavy-precipitation occurrences; the maximum value of hourly rainfall is recorded as the maximum rain intensity. Within 24 h (08:00–08:00 the following day, Beijing Time), when short-duration heavy precipitation occurred at ≥ 1 national station or at ≥ 3 regional stations in the study area, it was recorded as one short-duration heavy-precipitation day. Based on this criterion, the occurrences of short-duration heavy precipitation in western Guanzhong from April to September during 2018–2024 were counted.

Fig. 1 Terrain and meteorological-station distribution in western Guanzhong

(a) Geographic location of western Guanzhong

(b) Terrain of western Guanzhong

Map annotations and legend: elevation/m; national meteorological stations; regional meteorological stations; Baoji City; Xianyang City; Inner Mongolia Autonomous Region; Ningxia Hui Autonomous Region; Gansu Province; Shaanxi Province; Shanxi Province; Henan Province; Sichuan Province; Chongqing City; Hubei Province.

Fig. 1 Distribution of terrain features and meteorological stations in the western Guanzhong region

A total of 2,474 occurrences were obtained, and quality control was performed on the hourly precipitation data[28]. First, preliminary screening was carried out according to climatic extreme values; data that did not pass the extreme-value test were not subjected to subsequent judgment. Temporal continuity checks and spatial internal consistency tests were then conducted in sequence. After quality control, 2,301 valid samples were screened out, accounting for 93.0% of the total. When the number of stations with short-duration heavy precipitation on the same day was ≥ 50, it was recorded as one regional short-duration heavy-precipitation weather process. In total, 11 regional short-duration heavy-precipitation weather processes were selected (Table 1).

1.4 Research Methods

According to the terrain-precipitation model and the theory of slope-direction differences in the solar-radiation budget proposed by Fu Baopu[29–31], the dynamic and thermal uplift effects of terrain on short-duration heavy precipitation were quantitatively calculated. A multivariate regression fitting method was then used to calculate the influence coefficients of terrain dynamic uplift, thermal uplift, and elevation on the distribution of precipitation[32]. The larger the influence coefficient, the greater the increase in precipitation at that station caused by terrain; conversely, the smaller the correlation coefficient, the smaller the increase in station precipitation attributable to terrain. To eliminate differences in the orders of magnitude among the factors, each variable in every process was standardized using range standardization.

(1) Standardization of precipitation amount R_i

$$R_i = (r_i - r_{\min}) \,/\, (r_{\max} - r_{\min}) \tag{1}$$

where R_i represents the degree to which the precipitation amount at the station deviates from the mean value; r_i represents the precipitation amount at the station in each process; $r_{\min}$ represents the minimum precipitation amount in each process; and $r_{\max}$ represents the maximum precipitation amount in each process.

(2) Terrain dynamic uplift P_i

According to the studies of Fu Baopu[19] and Zhou Xueyun et al.[32], assume that the slope gradient of a given slope is α (°), the slope aspect is θ (°), the horizontal wind direction is A (°), and the wind speed is V ($\mathrm{m \cdot s^{-1}}$). The horizontal wind is decomposed into two components: V_n, normal to the slope direction, and V_s, parallel to the slope direction. Among them, the wind component V_s parallel to the slope is not affected by the slope and does not generate dynamic uplift, whereas the slope-facing wind component V_n, forced dynamically upward by the slope surface, can be further decomposed into the wind speed V_s' blowing upward along the slope surface and the wind speed V_n' blowing perpendicular to the slope surface. The wind speed V_n' perpendicular to the slope surface loses most of its kinetic energy through frontal collision with the slope or is converted into turbulent kinetic energy, and does not produce a systematic component in any particular direction. Therefore, the only wind speed that can cause the airflow to rise is V_s', which blows upward along the slope surface; that is, the terrain uplift velocity V_g. The calculation formula is as follows:

$$V_g = V_s' \cdot \sin\alpha = V_n' \cdot \cos\alpha \sin\alpha = \frac{V}{2}\cos(\theta - A)\sin 2\alpha \tag{2}$$

where $\sin 2\alpha$ is the slope-gradient influence factor, and $\cos(\theta - A)$ is the slope-aspect influence factor. When $0^\circ < \alpha \leq 45^\circ$, the greater the slope gradient, the more significant the enhancement effect on precipitation, with the maximum enhancement effect occurring at $\alpha = 45^\circ$. When $\alpha > 45^\circ$, the greater the slope gradient, the smaller the enhancement effect. When $|\theta - A| < 90^\circ$, the slope is windward and has a positive feedback effect on precipitation; when $|\theta - A| > 90^\circ$, it is a leeward slope and has a negative feedback effect on precipitation.

The vector-average method[33-34] was used to calculate the mean wind speed V and mean wind direction A during each precipitation period. V was further decomposed into mutually perpendicular zonal and meridional components, U_a and V_a. The calculation formula is as follows:

$$\begin{cases} U_a = \dfrac{1}{n}\sum_{i=1}^{n} U_i \\ V_a = \dfrac{1}{n}\sum_{i=1}^{n} V_i \end{cases} \tag{3}$$

The synthesized mean wind direction is:

$$A = (270 - \text{atan2}(V_a, U_a) \times 180/\pi)\%360 \tag{4}$$

where $\text{atan2}(V_a, U_a)$ is the argument function for computing a complex number, and % denotes the modulo operation.

The mean wind speed is:

$$V = \sqrt{U_a^2 + V_a^2} \tag{5}$$

It should be noted that, when the height of the horizontal wind exceeds the terrain slope height,

Table 1 Eleven regional short-duration heavy-precipitation events in the western Guanzhong region from 2018 to 2024
Tab. 1 Eleven regional short-term heavy rainfall events in the western Guanzhong region from 2018 to 2024

No.	Date / year-month-day	Station-times / times	Hourly extreme / mm	Station ID	Station name	Longitude	Latitude	Elevation / m
1	2018-08-21	111	54.5	V7069	Linyou Getousi	107.698°E	34.811°N	1447
2	2020-08-06	71	82.7	V7030	Fengxiang Liulin	107.308°E	34.559°N	848
3	2020-08-07	51	58	V0906	Xingping Nanshi	108.464°E	34.358°N	515
4	2022-07-12	108	49.8	V0314	Xunyi Tuqiao	108.428°E	35.014°N	1874
5	2022-07-15	106	77.3	V0555	Sanyuan Ma'e	108.933°E	34.823°N	624
6	2023-07-27	116	64.4	57024	Qishan	107.649°E	34.435°N	670.7
7	2023-07-28	56	46.3	V0208	Binzhou Chejiazhuang	107.907°E	34.984°N	1276
8	2023-08-06	70	59.2	57024	Qishan	107.649°E	34.435°N	670.7
9	2024-07-16	129	54.5	V7069	Linyou Getousi	107.698°E	34.811°N	1447
10	2024-08-07	70	82	V0554	Sanyuan Xiyang	109.003°E	34.661°N	422
11	2024-08-08	87	38.7	V7120	Mei County Qinghua	108.003°E	34.188°N	506

…at that altitude, the terrain no longer produces effective lifting of the airflow at that level. The reference heights of the standard pressure levels 925 hPa, 850 hPa, and 700 hPa correspond to approximately 700 m, 1 400 m, and 3 000 m, respectively. Considering the elevations corresponding to the terrain of western Guanzhong as a whole, only the wind field below 850 hPa is blocked by terrain; 700 hPa is already higher than the local terrain height and is not subject to direct dynamic lifting by terrain. For the upper-air wind field at each station, the neighborhood method was used. Hourly wind-speed and wind-direction data at four levels—1 000 hPa, 950 hPa, 925 hPa, and 850 hPa—were selected. According to formulas (4) and (5), the mean wind speed and mean wind direction at each station during the main precipitation period of each process were obtained; then the lifting value of terrain for the horizontal wind, V_g, was calculated and subjected to min–max normalization to obtain the dynamic lifting value P_i. The calculation formula is as follows:

$$P_i = (V_g - V_{g\,\min})/(V_{g\,\max} - V_{g\,\min}) \tag{6}$$

(3) Terrain thermal lifting A_i

Under ideal conditions, the astronomical solar-radiation value at each station can be obtained by calculation, whereas the thermal condition of the actual terrain is usually lower than this ideal value. To reduce computational complexity, this paper directly uses the sunshine duration of the day to calculate the thermal lifting condition corresponding to the terrain, and performs min–max normalization for each individual case to obtain the thermal lifting value A_i. The calculation formula is given in formula (7). The sunshine duration at each station is approximated by the national station in the administrative county or district to which it belongs.

$$A_i = q_i \times a_i \tag{7}$$

In the formula, q_i represents the percentage anomaly of the sunshine duration at that station on that day within this case; a_i represents the astronomical solar-radiation ratio of that station (Table 2).

According to the studies of Fu Baopu et al.

29–31

, the total astronomical solar radiation received by slopes differs with latitude and season. In summer, the ratios of the total astronomical solar radiation received by slopes of different gradients and aspects near 35°N to the obtainable value on a horizontal surface at the same latitude are shown in Table 2. Taking the eight principal directions as the centers,

Table 2 Ratio of total astronomical solar radiation received by slopes of different gradients and aspects at 35°N in summer to the obtainable value on a horizontal plane at the same latitude
Tab. 2 Ratio of total astronomical solar radiation received at 35°N in summer to that at the same latitude and elevation

Slope gradient/aspect	South-facing slope	Southeast (southwest) slope	East (west) slope	North-facing slope	Northeast (northwest) slope
5°	1.010	1.000	1.000	0.981	1.000
10°	1.014	1.010	0.992	0.956	0.976
20°	1.001	1.003	0.973	0.884	0.917

Slope gradient/aspect	South-facing slope	Southeast (southwest) slope	East (west) slope	North-facing slope	Northeast (northwest) slope
30°	0.960	0.977	0.942	0.784	0.837
40°	0.893	0.931	0.902	0.661	0.751
50°	0.801	0.866	0.850	0.518	0.659
60°	0.688	0.784	0.787	0.368	0.552

and extending 22.5° to each side, eight slope-aspect intervals are formed: the north-facing slope is 337.5°–22.5°, the northeast-facing slope is 22.5°–67.5°, the east-facing slope is 67.5°–112.5°, the southeast-facing slope is 112.5°–157.5°, the south-facing slope is 157.5°–202.5°, the southwest-facing slope is 202.5°–247.5°, the west-facing slope is 247.5°–292.5°, and the northwest-facing slope is 292.5°–337.5°. It can be seen that, at gradients below 20°, the total astronomical solar radiation received by south-facing and southeast- (southwest-) facing slopes is slightly higher than that on flat ground; on east- (west-) facing slopes, north-facing slopes, and northeast- (northwest-) facing slopes, the total astronomical solar radiation received decreases as the slope gradient increases.

(4) Altitude H_i

The altitude data H of each station are subjected to min–max normalization to obtain H_i, eliminating the influence of units on the data. This variable is a fixed value, and the calculation formula is as follows:

$$H_i = (H - H_{\min})/(H_{\max} - H_{\min}) \tag{8}$$

2 Results and Analysis

2.1 Temporal distribution of short-duration heavy precipitation

2.1.1 Interannual variation During the warm seasons (April–September) from 2018 to 2024, short-duration heavy precipitation in western Guanzhong occurred on a total of 123 d and 2 301 station-times, with an annual average of 329 station-times. The average number of short-duration heavy-precipitation events at a single station was relatively small, at 0.9. The proportion of short-duration heavy-precipitation occurrences showed a significant increasing trend ($P \leq 0.01$) (Fig. 2a). This may be because, against the background of climate warming, rising sea-surface temperatures in the tropical Pacific have strengthened the western Pacific subtropical high, which in turn enhances the East Asian summer monsoon and transports more water vapor northwestward

. Among the years, short-duration heavy precipitation was abnormally scarce in 2019, with 92 station-times and 11 d, accounting for 4.0% and 8.9%, respectively.

In 2024, short-duration heavy precipitation was abnormally frequent: the number of precipitation occurrences was 582 station-times, accounting for 25.3%, and the number of precipitation days was 28 d, accounting for 22.8%. From the annual distribution of hourly rainfall-intensity extremes, only the maximum rainfall intensity in 2019 was relatively small, at 49.0 mm $\cdot$ h^{-1}; in all other years, the maximum rainfall intensity exceeded 75 mm $\cdot$ h^{-1}, with the maximum being 88.0 mm $\cdot$ h^{-1} (2020). Among all short-duration heavy-precipitation events, rainfall intensity of 20–30 mm $\cdot$ h^{-1} accounted for the largest proportion, 69.5%, followed by 30–40 mm $\cdot$ h^{-1}, accounting for 20.6%; rainfall intensity above 40 mm $\cdot$ h^{-1} accounted for only 9.7% (Fig. 2d).

2.1.2 Seasonal variation Short-duration heavy precipitation in western Guanzhong occurred in all months from April to September, with the earliest occurrence on April 13 and the latest on September 23. The monthly variation showed a clear unimodal distribution (Fig. 2b). In April, the proportion of short-duration heavy-precipitation occurrences was only 0.96%, and the proportion of precipitation days was 2.4%. In May–June, short-duration heavy precipitation increased slightly, with occurrence proportions of 3.0% and 5.0%, respectively, and rainfall intensity also strengthened slightly. July had the most occurrences: short-duration heavy precipitation occurred 1 151 station-times, accounting for 50.0%, and occurred on 48 d, accounting for 39.0%. In August, the precipitation frequency decreased slightly, with 882 station-times, accounting for 38.3%, and 43 d, accounting for 35.0%. After entering September, short-duration

(a) Interannual variation (b) Seasonal variation (c) Diurnal variation (d) Proportion under different rainfall intensities

Fig. 2 Temporal variation of short-term heavy precipitation and the proportion under different rainfall intensities in the western Guanzhong region from 2018 to 2024

The number of heavy-precipitation events decreased rapidly, accounting for 2.7%, and the proportion of precipitation days was 4.1%. Although short-term heavy-precipitation events were mainly concentrated in July–August, the maximum rainfall intensity in May, June, and September could also exceed 50 mm $\cdot$ h^{-1}, showing the characteristics of high intensity and strong extremity. Therefore, attention should also be paid to these events in forecasting and early-warning services for severe convective weather.

Short-term heavy precipitation occurred most frequently in July–August, accounting for as much as 88.4%. An analysis of the ten-day distribution of short-term heavy precipitation during this period showed that occurrences were relatively few in early July, mid-August, and late August, accounting for 6.1%, 8.2%, and 9.0%, respectively; whereas events occurred more frequently from mid-July to early August, with the highest proportion in mid-July, at 26.7%. Thus, mid-July to early August is the key period requiring attention in short-term heavy-precipitation forecasting for the western Guanzhong region.

2.1.3 Diurnal variation

The diurnal variation in the occurrence frequency of short-term heavy precipitation in the western Guanzhong region exhibits a distinct bimodal pattern (Fig. 2c). The period from 18:00 to 23:00 is the concentrated occurrence period of short-term heavy precipitation, with each hourly time accounting for more than 6.5%. A secondary peak occurs from 04:00 to 05:00, with corresponding frequency proportions of 4.4% and 4.2%, while the proportions at all other times are less than 4.0%. Similarly, during the active period of short-term heavy precipitation from 18:00 to 23:00, the maximum rainfall intensity is also relatively large, exceeding 75 $mm \cdot h^{-1}$ at each time. However, the maximum rainfall intensity at 01:00, 03:00, 04:00, and 07:00 also exceeds 70 $mm \cdot h^{-1}$. This may be due to the formation of nocturnal ultra-low-level jets, which strengthen the transport of southwesterly airflow and lead to enhanced rainfall intensity in the western Guanzhong region after nightfall[^36]. Therefore, special attention should also be paid to this in short-term heavy-precipitation forecasting and early warning.

2.2 Spatial distribution of short-term heavy precipitation

The spatial distribution of warm-season short-term heavy precipitation in the western Guanzhong region has clear regional characteristics (Fig. 3a). High-frequency areas with more than 10 occurrences are located on the northern loess tablelands and the northern foothills of the western Qinling Mountains, whereas low-frequency areas are located in the southeastern plain region. In terms of precipitation extremes (Fig. 3b), the maximum rainfall intensity of short-term heavy precipitation is 88.0 $mm \cdot h^{-1}$. At most stations, the maximum rainfall intensity is below 50 $mm \cdot h^{-1}$; areas with large values above 50 $mm \cdot h^{-1}$ are mostly distributed along the northern foothills of the Qinling Mountains and the alluvial plain of the middle reaches of the Weihe River, with a few located on the northern loess tablelands. Compared with the high-frequency areas, their spatial distribution is more dispersed.

A further comparison of the spatial distribution of daytime and nighttime short-term heavy precipitation in the western Guanzhong region (Fig. 4a, Fig. 4b) shows that 1,093 station-times of short-term heavy precipitation occurred during the daytime, accounting for 47.5%. The spatial distribution of high-frequency areas is relatively dispersed, all located north of the Weihe River basin, with the area around Qishan as the strongest center. At night, 1,208 station-times occurred, accounting for 52.5%. The high-frequency areas are relatively concentrated, mainly in the northern loess tableland region, with the area around Yongshou as the strongest center. From the small···

Note: The red, yellow, and purple rectangular boxes indicate the three high-frequency areas: the loess tableland area, the plain area, and the Qinling mountainous area, respectively.

Figure 3 Spatial distribution of the frequency of short-term heavy rainfall events and maximum rainfall intensity in the western Guanzhong region from 2018 to 2024

Fig. 3 Spatial distribution of frequency and maximum rainfall intensity of short-term heavy rainfall events in the western Guanzhong region from 2018 to 2024

Figure 4 Spatial distribution of the frequency of daytime and nighttime short-term heavy rainfall events (a, b) and rainfall intensity of events with intensity \$ \$40 $\mathrm{mm \cdot h^{-1}}$ (c, d) in the western Guanzhong region from 2018 to 2024

Fig. 4 Spatial distribution of frequency (a, b) and maximum rainfall intensity (c, d) of short-term heavy rainfall characteristics in the western Guanzhong region from 2018 to 2024

Judging from the spatial distribution of heavy rainfall with hourly intensity \$ \$40 $\mathrm{mm \cdot h^{-1}}$ (Fig. 4c, Fig. 4d), daytime rainfall of this magnitude all occurred north of the Weihe River, totaling 112 station-times, of which 73.2% (82 station-times) were concentrated during 12:00–20:00, consistent with the characteristics of thermally driven convection. At night, rainfall of this magnitude was more widely distributed, covering all areas, with a total of 115 station-times; among them, 81.7% (94 station-times) were concentrated during 20:00–04:00.

The spatiotemporal distribution characteristics of short-term heavy rainfall in western Guanzhong not only reflect some common features of the eastern part of Northwest China, but also show the typical particularity of a region where the monsoon margin and complex terrain are interwoven. Consistent with the overall characteristics of Northwest China—"strong nocturnal rainfall and prominent locality" [1]—short-term heavy rainfall in western Guanzhong occurs frequently at night, while afternoon thermal convection is also relatively active, showing a diurnal variation pattern in which both daytime and nighttime rainfall are important. At the same time, the high-frequency areas of short-term heavy rainfall in western Guanzhong are distributed over the northern loess tableland and the northern foothills of the western Qinling Mountains. This is basically consistent with the tendency for short-term heavy rainfall in the eastern part of Northwest China to concentrate near mountains. However, compared with the neighboring arid area of the Longdong Loess Plateau [4,13], the high-frequency areas of short-term heavy rainfall in western Guanzhong are more concentrated, rainfall intensity is greater, and the nocturnal rainfall characteristics are more pronounced. Therefore, local forecasting and early warning should comprehensively consider diurnal differences, seasonal evolution, and the combined effects of complex underlying surfaces.

2.3 Analysis of the Mechanism of Topographic Influence

2.3.1 Relationship Between Short-Term Heavy Rainfall and Topography

To investigate the relationship between geographic location, such as longitude and latitude, and topographic factors, such as slope, aspect, and elevation

⋯degree) on short-term heavy rainfall in western Guanzhong, principal component analysis was used to reduce the dimensionality of the variables and eliminate possible collinearity interference among them, thereby extracting the three principal components with the highest variance contributions: the first principal component (P_1) is a macroscopic physiographic factor dominated by elevation and latitude; the second principal component (P_2) is a geographic-location factor composed of longitude and latitude; and the third principal component (P_3) is an integrated terrain-impact factor composed of the slope-impact factor and the aspect-impact factor. The variance inflation factors (VIF) of the three principal components were all equal to 1, indicating that the principal components were completely independent of one another and that no collinearity problem existed. Based on the above three principal components, linear regression analyses were conducted for the frequency and extreme values of short-term heavy rainfall. The results show that, for the extreme values of short-term heavy rainfall, none of the three principal components exhibited a significant influence, indicating that the extreme rainfall intensity in this region may be governed by mesoscale dynamical processes within the convective system itself. For the frequency of short-term heavy rainfall, the macroscopic physiographic factor (P_1) made a significant positive contribution, with an influence coefficient of 0.240; the geographic-location factor (P_2) made a negative contribution, with an influence coefficient of −0.147, and both reached the extremely significant level ($P \leq 0.01$). By contrast, the positive contribution of the integrated terrain-impact factor (P_3) was relatively small, with an influence coefficient of 0.030, and it did not pass the significance test.

To clarify the specific effects of terrain slope, aspect, and elevation on short-term heavy rainfall, 11 regional short-term heavy rainfall events were selected. For each station, the terrain dynamic uplift effect value P_i, the thermal uplift effect value A_i, and the elevation value H_i were calculated. Using multiple linear regression, the correlations between the rainfall amount R_i in each event and P_i, A_i, and H_i were analyzed (Table 3). It can be seen that the correlation between P_i and R_i was the weakest and basically did not pass the significance test; A_i had a positive correlation with R_i; and H_i had the best correlation with R_i. This indicates that, during short-term heavy rainfall weather processes in western Guanzhong, station elevation has the greatest influence on short-term heavy rainfall, the terrain' s thermal uplift effect ranks second, and the terrain' s dynamic uplift effect has the smallest influence. Correspondingly, in the 11 regional short-term heavy rainfall events, the elevations of the stations with precipitation extreme values were distributed at about 670.7 m (Fig. 5a), while the lifting condensation level (LCL) averaged about 850 m. This indicates that only weak uplift conditions are needed for water vapor in the air to cool and condense to form cloud droplets; moreover, the cloud-base height is relatively low, almost close to the ground, so evaporation loss during the falling process of cloud droplets is relatively small, improving precipitation efficiency.

Further analysis of the relationship between station elevation and short-term heavy rainfall found that short-term heavy rainfall exhibits a unimodal pattern with increasing elevation (Fig. 5b). The proportion of short-term heavy rainfall is highest at 400–700 m, reaching 36.1%, followed by 700–1000 m and 1000–1300 m, with proportions of 26.2% and 25.9%, respectively. When elevation exceeds 1300 m, short-term heavy rainfall decreases as elevation increases. At elevations below 400 m and above 1300 m, the maximum rainfall intensity is relatively small, at 62.1 $mm \cdot h^{-1}$ and 49.8 $mm \cdot h^{-1}$, respectively. Within the 400–1300 m elevation range, maximum rainfall intensities all exceeded 80 $mm \cdot h^{-1}$.

2.3.2 Analysis of influence mechanisms

The distributions of elevation, terrain slope, and aspect in the high-incidence area of short-term heavy rainfall in western Guanzhong were analyzed (Fig. 1, Fig. 6). Overall, the terrain is higher in the west and lower in the east, and higher in the north and south but lower in the middle. The terrain has marked uniqueness: it lies between the Liupan Mountains on the northwest side and the Qinling Mountains on the south side, forming a "trumpet-shaped" narrow-tube channel.

In the northern loess tableland region, the elevation is 700–1800 m, the terrain is relatively high, and the relief is comparatively gentle, dominated by gentle slopes or inclined slopes. The aspects are mostly north-facing or northwest-facing, and the areas with these aspects are relatively concentrated. The station elevations in this region are close to or exceed the atmospheric lifting condensation level; combined with the uplift effect of sloping terrain on airflow, this makes warm, moist airflow more likely to rise and cool, thereby readily producing persistent con—

Table 3 Linear regression of 11 regional short-term heavy rainfall events in western Guanzhong

Date / year-month-day	Frequency / times	Extreme value / mm	Dynamic uplift influence coefficient	Dynamic uplift Sig	Thermal uplift influence coefficient	Thermal uplift Sig	Elevation influence coefficient	Elevation Sig
2018-08-21	111	54.5	0.041	0.458	0.023	0.705	0.033	0.555

Date / year-month-day	Frequency / times	Extreme value / mm	Dynamic uplift influence coefficient	Dynamic uplift Sig	Thermal uplift influence coefficient	Thermal uplift Sig	Elevation influence coefficient	Elevation Sig
2020-08-06	71	82.7	−0.099	0.086	−0.315**	0.000	−0.270**	0.000
2020-08-07	51	58	−0.029	0.573	−0.066	0.210	−0.380**	0.000
2022-07-12	108	49.8	−0.025	0.644	–	–	0.138**	0.013
2022-07-15	106	77.3	−0.125**	0.024	0.033	0.660	0.049	0.405
2023-07-27	116	64.4	0.019	0.729	–	–	−1.408	0.160
2023-07-28	56	46.3	−0.021	0.702	0.133**	0.018	0.134**	0.017
2023-08-06	70	59.2	0.018	0.744	−0.115	0.059	0.098	0.108
2024-07-16	129	54.5	−0.075	0.167	0.127	0.907	0.206**	0.000
2024-08-07	70	82	−0.007	0.894	−0.097	0.078	−0.290**	0.000
2024-08-08	87	38.7	0.049	0.374	0.188**	0.001	−0.014	0.800

Note: "–" indicates that the sunshine duration on that day was 0 and there was no thermal uplift; ** indicates passing the extremely significant level test ($P \leq 0.01$).

Fig. 5 Altitude distribution of the stations recording the maximum rainfall intensity during regional events (a), and variation of short-term heavy rainfall with altitude (b), in the western Guanzhong region.

- **(a) Altitude of stations with the maximum rainfall intensity**
  - Legend: altitude; median
  - Vertical axis: altitude / m
  - Horizontal axis: date / year-month-day
  - Dates: 2018-08-21; 2020-08-06; 2020-08-07; 2022-07-12; 2022-07-15; 2023-07-27; 2023-07-28; 2023-08-06; 2024-07-16; 2024-08-07; 2024-08-08
- **(b) Variation of short-term heavy rainfall with altitude**
  - Legend: frequency; maximum rainfall intensity
  - Left vertical axis: proportion of short-term heavy-rainfall occurrences / %
  - Right vertical axis: maximum rainfall intensity / (mm h^{-1})
  - Horizontal axis: altitude / m
  - Altitude classes: ≤ 400; $(400 \sim 700]$; $(700 \sim 1000]$; $(1000 \sim 1300]$; $(1300 \sim 1600]$; > 1600

Fig. 6 Spatial distribution of slope and aspect in the western Guanzhong region.

- **(a) Slope**
  - Legend: slope / (°)
  - Classes: < 2 (flat); $2 \sim 5$ (gentle flat slope); $5 \sim 15$ (gentle slope); $15 \sim 25$ ([[unclear: slope class label]]); $25 \sim 35$ (steep slope); $35 \sim 40$ (steep slope); $40 \sim 45$ (very steep slope); > 45 (precipitous slope)
  - Map labels: Baoji City; Xianyang City; N; 0–40 km
- **(b) Aspect**
  - Legend: aspect / (°)
  - Classes: -1 (flat land); $0 \sim 45$ (northward); $45 \sim 135$ (eastward); $135 \sim 225$ (southward); $225 \sim 315$ (westward); $315 \sim 360$ (northward)
  - Map labels: Baoji City; Xianyang City; N; 0–40 km

convective rainfall (red rectangle in Fig. 3a).

In the central Weihe River alluvial plain, the elevation is 360–700 m, and the terrain is broad and flat. The area is dominated by flat land or gentle slopes with gradients $< 5°$; in terms of aspect, east-facing and south-facing slopes account for higher proportions. The ability of this terrain to lift airflow vertically is limited, and the dynamic conditions for water-vapor condensation are insufficient, so precipitation is relatively less affected by topography. It is worth noting that this area contains densely built urban districts, such as the main urban area of Xianyang and the eastern urban district of Baoji, as well as dense population concentrations. The urban heat-island effect is significant [37]. In summer afternoons, thermal differences between urban and suburban areas are conducive to the formation of urban mesoscale airflow convergence centers. Meanwhile, thermal uplift strengthens the vertical shear in the boundary layer, making it easier to trigger localized convective rainfall (yellow rectangle in Fig. 3a).

In the mountainous area on the northern foot of the southern Qinling Mountains, the elevation is 650–2000 m, and the terrain drops markedly from south to north. The area is dominated by steep slopes with gradients $> 25°$, and some valleys and mountain-margin areas have precipitous slopes above 35°. North-facing slopes account for an extremely high proportion and are distributed in a continuous belt. The terrain in this area is steep, producing a pronounced lifting effect on airflow. Forced uplift enhances large-scale vertical motion and forms orographic convergence or lee waves, providing favorable conditions for the release of unstable energy [38]. Together with mountain blocking and local thermal effects, these processes promote rainfall enhancement. In addition, north-facing slopes receive weaker solar radiation and have lower air temperatures, so the air more readily reaches saturation and triggers local convection, although the intensity is limited (purple rectangle in Fig. 3a).

The mechanism by which topography affects precipitation in western Guanzhong differs from that associated with independent giant mountain systems such as the Qilian Mountains and the Qinling Mountains. The extensive windward slopes of the Qilian Mountains and the Qinling Mountains systematically lift warm, moist summer-monsoon airflow and westerly water vapor, making it easy to form relatively stable, broad-coverage zones of persistent precipitation in the middle section of the Qilian Mountains [39] and on the southern foot of the Qinling Mountains [40]. In contrast, the "trumpet-shaped" terrain of western Guanzhong forces the small amount of water vapor carried by the westerly system to couple there with warm, moist southwesterly airflow. Together with small- and mesoscale topographic uplift, this leads to the rapid superposition and release of energy, forming a sudden, localized mesoscale zone of enhanced precipitation.

3 Conclusions and Discussion

This paper takes short-term heavy rainfall in western Guanzhong as the study object, analyzes the spatiotemporal distribution characteristics of short-term heavy rainfall, and explores its relationship with topography.

relations, and quantitatively analyzed the effects of topographic dynamic uplift, thermal uplift, elevation, and other factors on the distribution of short-duration heavy precipitation. The main conclusions are as follows:

(1) During the warm seasons (April–September) of 2018–2024, the proportion of short-duration heavy precipitation events in western Guanzhong showed a clear increasing trend. Rainfall intensity was concentrated at $20 \sim 40\ \mathrm{mm \cdot h^{-1}}$. Such events occurred mainly from mid-July to early August, and the maximum rainfall intensity from May to September could exceed $50\ \mathrm{mm \cdot h^{-1}}$. The diurnal variation showed a distinct bimodal pattern; 18:00–23:00 was the most active period for short-duration heavy precipitation, with maximum rainfall intensities all exceeding $75\ \mathrm{mm \cdot h^{-1}}$.

(2) The spatial distribution of short-duration heavy precipitation in western Guanzhong was uneven. High-frequency areas were located on the north-

ern Loess tablelands and the northern foothills of the western Qinling Mountains, while low-frequency areas were located in the southeastern plain. The day–night spatial distributions of short-duration heavy precipitation were inconsistent. During the daytime, high-frequency areas were relatively dispersed, occurring in both the northern Loess tablelands and the Weihe River basin; heavy precipitation of $\geq$ 40 mm $\cdot$ h^{-1} occurred north of the Weihe River basin. At night, events mainly appeared in the northern Loess tablelands; the distribution of $\geq$ 40 mm$\cdot$h^{-1} was relatively scattered, and such events occurred in every county.

(3) Geographic location and topographic factors had no obvious influence on the distribution of maximum rainfall intensity for short-duration heavy precipitation in western Guanzhong, but they had a significant influence on the frequency distribution, mainly through elevation, latitude, and longitude. Elevation had the greatest effect on short-duration heavy precipitation, followed by terrain-induced thermal uplift, while terrain-induced dynamic uplift had the smallest effect. Short-duration heavy precipitation exhibited a unimodal pattern with increasing elevation. It occurred mainly at elevations of 400–1300 m, where maximum rainfall intensities all exceeded 80 mm $\cdot$ h^{-1}; above 1300 m, short-duration heavy precipitation decreased with increasing elevation.

This study analyzed the spatiotemporal distribution characteristics of short-duration heavy precipitation in western Guanzhong and its relationship with terrain, but certain limitations remain. Observation stations are sparse in key terrain areas such as mountains and tablelands, which constrains the accurate capture of refined precipitation characteristics. In addition, the occurrence of short-duration heavy precipitation is jointly affected by synoptic-scale circulation patterns, mesoscale and small-scale system configurations, and complex terrain. Therefore, subsequent research will focus on introducing high-resolution reanalysis data, further analyzing the spatiotemporal distribution characteristics and terrain-influence mechanisms of short-duration heavy precipitation under different weather types, and exploring objective forecast-correction methods for short-duration heavy precipitation applicable to the local region.

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Spatiotemporal characteristics of short-time heavy rainfall in relation to topography in western Guanzhong, Shaanxi Province

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Abstract: Investigating the spatiotemporal characteristics of short-time heavy rainfall and its relationship with topography is crucial for developing regionally refined nowcasting models and enhancing risk assessment and prevention capabilities for extreme precipitation disasters. The spatiotemporal distribution of short-time heavy rainfall in western Guanzhong was analyzed using hourly precipitation data from 327 meteorological stations during the warm season (April–September) from 2018 to 2024, ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts, and 30 m digital elevation model data. The controlling roles of topography were investigated using inverse distance weighting, principal component analysis, and linear regression. The results indicate the following: (1) The frequency of short-time heavy rainfall events during the warm season increased between 2018 and 2024. The rainfall intensity predominantly ranged from 20 to 40 mm · h−1. The majority of events occurred between mid-July and early August, and the maximum recorded rainfall intensity exceeded 50 mm · h−1. The diurnal variation was bimodal, with the most active period between 18:00 and 23:00. (2) The spatial distribution was uneven: high-frequency rainfall areas were located in the northern high-altitude loess tableland and the northern foothills of the western Qinling Mountains, and low-frequency rainfall areas were located in the eastern low-altitude plains. Significant diurnal variation was observed. During the daytime, high-frequency areas were scattered primarily north of the Weihe River, whereas during the night they were concentrated on the northern loess tableland. (3) The frequency of the short-time heavy rainfall was significantly correlated with elevation, latitude, and longitude, with elevation the most dominant factor. Topographic thermal uplift played a secondary role, and dynamic lifting had the least influence. The short-time heavy rainfall showed a single-peak pattern with altitude, with most events occurring at altitudes between 400 and 1300 m. The frequency of short-time heavy rainfall above 1300 m decreased with increasing altitude. These findings provide a theoretical foundation for improving forecasting and the early warning of short-time heavy rainfall in the region.

Keywords: western Guanzhong; short-time heavy rainfall; hour scale; spatio-

temporal characteristics; topography

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