Statistical Characteristics and Synoptic Situations of Long-Duration Heavy Rainfall Events Over North China

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Abstract

The spatiotemporal characteristics of long-duration heavy rainfall (LDHR) events are statistically analyzed using hourly surface observations over central-southern North China during the warm seasons of 2011–2018, revealing pronounced variabilities in the frequency and amount of LDHR. Two accumulated rainfall peaks are found in the western (WHRR) and eastern (EHRR) regions of central-southern North China. The LDHR occurrence frequency decreases westward, and the peaks of the LDHR amount, frequency and intensity in the WHRR and EHRR are observed at nighttime (2100–0200 Beijing Standard Time) or in the early morning (0300–0700 Beijing Standard Time). The rainfall amount exhibits a bimodal diurnal variation in the WHRR (determined mainly by the rainfall intensity), whereas a single rainfall frequency-related peak is found in the EHRR. Four types of LDHR events corresponding to different flow patterns, synoptic systems, and moisture transport mechanisms are classified according to their locations. The first is heavy rainfall in the WHRR with an upper-level jet favorable for an ascending motion near Taihang Mountain; topographic blocking of southerly flow is crucial for heavy rainfall formation. The second describes heavy rainfall in the EHRR attributable to the favorable configurations of upper- and lower-level systems. Heavy rainfall occurs over both the WHRR and the EHRR in the third type, including topographic blocking and convergence associated with low-pressure systems or shear lines and a mesoscale low vortex or shear line related to topographic effects and positive vorticity advection in front of a westerly trough. The fourth shows a scattered distribution of LDHR stations and is generally not comparable to the first three types.

1. Introduction

In North China, heavy rainfall events occur mostly during the warm season (i.e., from May to September) and are responsible for a variety of severe catastrophes (Jiang & Xiang, 1997; Kang et al., 2019; You, 1965), such as urban flooding and landslides; these events lead to large amounts of damage, injuries, and even deaths. Therefore, analyses of long-duration heavy rainfall (LDHR) events are important for understanding and predicting high-impact weather phenomena.

The temporal and spatial variations in precipitation exhibit different characteristics from case to case among different locations and seasons. Rainfall events can be generally divided into long-duration (more than 6 hr) and short-duration (1–3 hr) events. In North China, long-duration rainfall events tend to reach the maximum hourly rainfall in the early morning, while short-duration events reach their peak rainfall in the late afternoon (Yu et al., 2007). Additional detailed research reveals that long-duration rainfall over North China presents peaks during 0200–0600 Beijing Standard Time (BST) (Yuan et al., 2014). Similarly, the monsoon rain belt over North China is dominated by long-duration rainfall with early morning peaks (Yuan et al., 2010). More than 60% of all rainfall over North China originates from long-duration rainfall events (Yu et al., 2007); accordingly, the decadal decreases in rainfall over North China during 1966–2005 are attributable to the reduction in long-duration rainfall events, especially rainfall occurring between midnight and morning (Li et al., 2011). Evidently, long-duration rainfall events contribute to an overabundance of accumulated rainfall in North China during the warm season.
A heavy rainfall event is usually the result of multiscale interactions across cloud-scale, mesoscale, and larger-scale systems under favorable synoptic conditions (Chen & Li, 1995; Houze, 2004; Houze et al., 1989; Iwasaki, 2015; Zhang et al., 2013; Zhong et al., 2015). This is especially true for LDHR events, in which the local topographic forcing and large-scale moisture supply play important roles. Numerous studies on heavy rainfall events in North China have been published over the past decade (Luo et al., 2016; Zhang & Zhai, 2011; Zheng et al., 2016). Under synoptic conditions, heavy rainfall events are divided into several types that have been discussed in terms of their dynamics, thermodynamics, and water vapor supply (Sun et al., 2005; Wang et al., 2014; Yang et al., 2016). Regional heavy rainfall events in North China may be associated mainly with a low-level vortex, a shear line, a cold front with a trough, and occasionally a typhoon (Ding et al., 1980). An abundance of warm and moist air transported by strong southerly or easterly flows is important for heavy rainfall (Chen et al., 2014; Zhao et al., 2019). The instability and downward momentum transport caused by dry and cold air in the middle and upper troposphere play a significant role in the generation of heavy rainfall (Gao et al., 2010; Yang et al., 2009), although enhanced local upper-level divergence due to the reinforcement of the upper-level jet is also important (Zhao et al., 2011). Consequently, the analysis of heavy rainfall is essential for understanding heavy precipitation in both North China and south China (Li et al., 2018; Li et al., 2019).

Taihang Mountain (112.00–116.00°E, 35.00–40.25°N), which boasts an average elevation of approximately 1,000–1,500 m with peaks at 2,882 m, is located west of the North China Plain meridional, while Yimeng Mountain (116.90–118.85°E, 35.40–36.82°N) is located to the east (Figure 1a). Taihang Mountain exhibits a sharp gradient on its eastern slope (with an average slope of 4.8%, i.e., the elevation difference over the horizontal distance), which constitutes a natural barrier to low-level flow. Narrow and strong rain bands are often observed during heavy rain events (Cheng et al., 1993). The multiscale nature of the topography throughout North China complicates the temporal and spatial variations in the rainfall distribution (He & Chen, 2019; Li et al., 2017a; Tao, 1981; Zhu et al., 2018). In accordance with the location, intensity, and movement of rainstorms over Taihang Mountain, Yan (2013) classified summer torrential rains into five types: rainstorms to the east or west of Taihang, rainstorms over Taihang Mountain, rainstorms on both sides, and rainstorms that weaken upon crossing Taihang Mountain. The occurrence and development of heavy precipitation varies with synoptic circulation. In particular, Taihang Mountain plays an important role in the triggering (Huang et al., 2012; Li et al., 2017b) and amplification (Sun, 2005) of mesoscale convective systems. When conditionally unstable easterlies impinge on the mountain, the low-level flow may be uplifted or blocked. The location of heavy rainfall varies with the wind direction and speed and can occur over the mountaintop, slope, and mountain foot (Jiang & Xiang, 1997; Kang et al., 2019; You, 1965). Generally, the spatiotemporal features of rainfall are highly correlated with elevation in North China.
(Shi, 1981), and Taihang Mountain demonstrates especially important impacts on the intensity, distribution, and duration of heavy rainfall (Sheng et al., 2012; Wang et al., 2018).

In contrast, Yanshan Mountain (115.67°–119.83°E, 39.75°–41.00°N), located in northern North China, is aligned in a nearly zonal direction with a gentle slope (1.8% on average). Significant differences in climate and topographical features are found between the northern and southern parts of North China. Heavy rainfall over central and northern North China is mostly affected by a local sea-land breeze and an eastward return current in return flow events (Song et al., 2017). However, a mountain with irregular topography and a gentle slope do not constitute a continuous terrain barrier to low-level flow. Consequently, a strong precipitation zone is observed over a broad region of the northern slope of Yanshan Mountain (Cheng et al., 1993). Beijing is located at the junction between Taihang Mountain and Yanshan Mountain, and its unique topographical features and urbanization have significant impacts on rainfall (Li et al., 2017c; Miao et al., 2011; Sun & Yang, 2008). Numerous studies have been carried out to illustrate the heavy rainfall in northern North China (Wilson et al., 2007; Xiao et al., 2019; Yang et al., 2014; Yu et al., 2017; Zhang et al., 2013; Zhong et al., 2015), but few researchers have investigated the heavy rainfall over central-southern North China (C-SNC). Hence, this study investigates the spatiotemporal statistical characteristics and features, for example, the topography and synoptic conditions, governing the distribution of LDHR precipitation over C-SNC.

The data and methodology used in this study are described in the next section, and the temporal and spatial characteristics of LDHR events are presented in section 3. A classification of the statistics of LDHR events is shown in section 4. In section 5, we describe the synoptic situations associated with the classified LDHR events, and a summary and conclusions are given at the end.

2. Data and Methodology

2.1. Data

A dense automatic weather station (AWS) network is beneficial to statistical analyses of LDHR events in North China. In this study, quality-controlled observational data with a 1 hr interval during 2011–2018 from 2,781 AWSs over C-SNC (obtained from the National Meteorological Information Center China (NMIC, http://data.cma.cn/)) are used to analyze the spatiotemporal characteristics of LDHR events. European Centre for Medium-Range Weather Forecasts Interim Reanalysis (ERA-Interim) data (Dee et al., 2011) are used to verify the large-scale circulations and synoptic patterns for LDHR events. The ERA-Interim data provide atmospheric variables four times per day (0200, 0800, 1400, and 2000 BST) with a spatial resolution of 0.25° × 0.25°. The variables used herein include horizontal wind, vertical velocity, geopotential height, temperature, specific humidity, and horizontal divergence. The pseudoequivalent potential temperature (θse) and total precipitable water vapor (PW) are calculated based on the basic reanalysis data. Vertical sounding data (available from NMIC, China) of the temperature, pressure, relative humidity, wind direction, and wind speed at Xingtai (114.37°E, 37.18°N) are also used for a typical case analysis.

2.2. Methodology

A rainfall event begins when the hourly rainfall is more than or equal to 0.1 mm and ceases when the hourly rainfall is less than 0.1 mm for 2 hr. A 20 mm h⁻¹ rainfall rate was defined by Zhang and Zhai (2011) as a reasonable criterion for short-duration heavy rainfall events in China, and the long-duration rainfall event was defined as lasting more than 6 hr (Yu et al., 2007). Here, we define an LDHR event as having a maximum hourly rainfall exceeding 20 mm and a duration surpassing 6 hr. The annual average LDHR rainfall frequency (amount) is the mean number (accumulated rainfall) of LDHR events during the warm season.

The accumulated hourly rainfall amount, frequency, and intensity are calculated according to the hour without distinguishing the date, that is,

\[ p^i = \left( \frac{\sum_{k=i-1}^{K} \sum_{j=1}^{J_k} P_{kj}}{N_{kj}} \right), \]

\[ f^i = \left( \frac{\sum_{k=i-1}^{K} \sum_{j=1}^{J_k} n_{kj}}{N_{kj}} \right), \]

where \( P_{kj} \) is the hourly rainfall amount (mm), \( n_{kj} \) is the hourly occurrence frequency, and \( N_{kj} \) is the total occurrence frequency of the rainfall event.
3. Temporal and Spatial Characteristics of LDHR Events

Figures 1a and 1b show the spatial distributions of the annual average rainfall amount during LDHR events and the corresponding annual average rainfall frequency, respectively. The strongest rainfall amount (≥160 mm) occurs primarily over the western and eastern parts of C-SNC, while the rainfall amount in the middle of the region is obviously weak. In the western heavy rainfall region (WHRR), a narrow meridional zone of weak rainfall is observed in the vicinity of Taihang Mountain. North of 38.5°N, the stations with heavy rainfall are concentrated in the piedmont plain; south of 38.5°N, the heavy rainfall stations extend from the piedmont plain to the hillside of Taihang Mountain. The eastern heavy rainfall region (EHRR) is located in the eastern plain of C-SNC, where relatively uniform heavy rainfall is observed. The central weak rainfall region (CWR) is parallel to Taihang Mountain between the two abovementioned heavy rainfall regions, and precipitation over the CWR gradually increases with latitude. The frequency of LDHR events generally increases eastward, and LDHR occurs much more frequently in the EHRR than in the WHRR.

Investigating the spatial distributions of the annual average rainfall amount and frequency reveals that the diurnal variations in LDHR events over the WHRR and EHRR are noteworthy. For the convenience of data processing, the diurnal cycle of hourly rainfall is divided into four time periods: early morning (0300–0700 BST), noon (0800–1300 BST), afternoon (1400–2000 BST), and nighttime (2100–0200 BST). To highlight the characteristics of heavy rainfall over the WHRR and EHRR, the periods with the peak rainfall amount, peak frequency, and peak intensity for stations with annual average rainfall amounts exceeding 80 mm are plotted in Figure 2. Note that the 24 hr time series data of the hourly rainfall amount, frequency, and intensity within a day are first sorted by their quantities, and the top five data points are selected. Then, only the stations with three or more of the top five ranks in a 1 hr period are plotted as the selected color dots. Over the WHRR, the peak rainfall amount, frequency, and intensity occur mostly during nighttime (at 57.06%, 51.53%, and 46.01% of stations, respectively), followed by 17.79%, 27.61%, and 15.95%, respectively, in the early morning. The percentages of peaks with stations during the nighttime are evidently much higher than those with peaks in the early morning for all three quantities. In the EHRR, however, the percentages of stations with peak quantities in the early morning are 42.83%, 37.83%, and 31.74%, whereas 32.93%, 41.41%, and 26.30% of the stations exhibit peaks in the nighttime. Different characteristics are detected near the mountains and plain areas.

Although the number of heavy rainfall stations still displays the highest percentages during the nighttime, the percentages of stations with heavy rainfall amounts are decreased significantly in comparison to those in the early morning due to the weakened nighttime intensity. In the WHRR, the stations with heavy rainfall are distributed predominantly near the mountains during the afternoon and in the piedmont plain during
the nighttime. In the EHRR, however, the stations with heavy rainfall amounts have the highest percentages in the early morning. Hence, the stations with high percentages of heavy rainfall amounts shift from the WHRR in the afternoon and nighttime to the EHRR in the early morning, reflecting the eastward propagation of heavy rainfall from mountainous areas to the plain. This feature has been noted in previous studies on the diurnal variations in precipitation; for example, Yu and Li (2016) illustrated nighttime peaks in both the amount and the frequency of rainfall in the western North China Plain and an early morning peak over the eastern North China Plain. In the Yanshan and Taihang Mountains, the average peak of local precipitation appears early in the afternoon near the tops of the mountains and propagates downslope (southeastward). In the central North China Plain, where a broad area of nocturnal precipitation appears, the peak is reached around midnight or in the early morning (He & Zhang, 2010). The correlation coefficients between the amount and frequency/intensity are 0.23/0.57 in the WHRR and 0.24/0.43 in the EHRR. Accordingly, the spatial distribution of the rainfall amount is consistent with that of the rainfall intensity but is not closely related to that of the frequency over these two heavy rainfall regions; this difference is the result of accounting for a large proportion of LDHR events. Compared with that in the WHRR, the correlation between the amount and frequency of heavy rainfall in the EHRR is enhanced, but the correlation between the amount and intensity is slightly weakened. This finding demonstrates a decline in rainfall intensity over the plain. Heavy rainfall occurs more frequently over the plains than over the mountains, which is consistent with the illustration in Figure 1.

Figure 2. Spatial distributions of the periods with the peak rainfall amount (a), peak frequency (b), and peak intensity (c) during the diurnally varying LDHR events over the WHRR and EHRR. The shading indicates topography.
Figure 3 shows the diurnal variations in the average rainfall amount, frequency, and intensity over the WHRR and EHRR. Note that only stations with an annual average rainfall exceeding 80 mm are considered. The averaged diurnal rainfall amount presents a typical bimodal distribution in the WHRR, as shown by the green line in Figure 3a, even if the two peaks show large differences. The main rainfall amount peak (1.35) occurs at 2300 BST, and the secondary peak (1.03) occurs at 0800 BST, while the minimum (0.67) appears at 1600 BST, after which the rainfall amount increases sharply. The rainfall amount and intensity show basically consistent diurnal variations with a correlation coefficient of 0.79. The average diurnal rainfall frequency presents a typical maximum at 0200 BST and a minimum at 1400 BST. The secondary precipitation peak is clearly a result of the strong rainfall intensity, despite its relatively low frequency. In the EHRR, the diurnal variation in the rainfall amount presents a typical maximum during the period between 0100 and 0900 BST (Figure 3b), which is highly consistent with the frequency with a correlation coefficient of 0.91. The rainfall amount increases slightly due to a secondary rainfall intensity peak at 1800 LST, which implies the contribution of convective rainfall in the afternoon during LDHR events. These results demonstrate that the diurnal variation in the rainfall amount is determined mainly by the rainfall intensity in the WHRR and by the rainfall frequency in the EHRR, similar to that the situation in eastern China (Zhou et al., 2008).

4. Statistical Classification of LDHR Events

To investigate the precipitation features associated with weather systems, the selected 169 LDHR events are divided into four categories according to the rainfall pattern. There are 534, 1,302, and 945 AWSs over the WHRR, EHRR, and the remaining regions, respectively, which are marked as \( n_1, n_2, \) and \( n_3 \). In a specific precipitation event, the total durations (in hours) of heavy rainfall (hourly rainfall \( \geq 20 \) mm) for all stations are \( m_1, m_2, \) and \( m_3 \) in the WHRR, EHRR, and the remaining regions, respectively. The weighted rate of hourly heavy rainfall in each of the regions is defined as follows:

\[
\text{Rate}_1 = \left( \frac{L}{n_1} \right) \times \frac{m_1}{m_1 + m_2 + m_3},
\]

(7)

\[
\text{Rate}_2 = \left( \frac{L}{n_2} \right) \times \frac{m_2}{m_1 + m_2 + m_3},
\]

(8)

\[
\text{Rate}_3 = \left( \frac{L}{n_3} \right) \times \frac{m_3}{m_1 + m_2 + m_3},
\]

(9)

where \( L/n_i (i = 1, 2, 3 \) and \( L = 1,300 \)) is a weight determined by the number of stations that normalizes the rates among the WHRR, EHRR, and the remaining regions. The following classification is proposed:

- **Type I:** if \( \text{Rate}_1 \geq \max (\text{Rate}_2, \text{Rate}_3) \) and \( \text{Rate}_1 \geq K \), heavy rainfall occurs mainly over the WHRR.
- **Type II:** if \( \text{Rate}_2 \geq \max (\text{Rate}_1, \text{Rate}_3) \) and \( \text{Rate}_2 \geq K \), heavy rainfall occurs mainly over the EHRR.
- **Type III:** if \( \text{Rate}_1 < K \) and \( \text{Rate}_2 < K \), but \( \text{Rate}_1 + \text{Rate}_2 \geq \text{Rate}_3 \) and \( \text{Rate}_1 + \text{Rate}_2 \geq K \), heavy rainfall occurs mainly in the WHRR and EHRR.
- **Type IV:** includes the rest of the LDHR events that do not fall into one of the above three types.
Table 1

Frequencies of the Four Types of LDHR Events Over C-SNC

| Type | Rate | Percentage |
|------|------|------------|
| I    | 32   | 19%        |
| II   | 81   | 48%        |
| III  | 34   | 20%        |
| IV   | 22   | 13%        |
| Total| 169  |            |

This classification is verified as reasonable when $K = 55\%$, which can effectively reflect the spatial distribution of the difference in total precipitation among the four types of LDHR events. The number of stations reaches 2,495, approximately 90% of all stations available, and the cumulative precipitation of the first three types can account for more than 70% of the total precipitation.

Table 1 shows the frequencies of the four types of LDHR rainfall classifications. Type II occurs most frequently with a frequency close to 50%. Types I and III display basically the same frequencies of 19% and 20%, respectively. The first three types include 87% of all occurrences, including most LDHR events over C-SNC.

5. Synoptic Situations Associated With LDHR Events

The spatial distributions of heavy rainfall among the three types are significantly different. In Type III, heavy rainfall may occur over both the WHRR and the EHRR at the same or different times. On the other hand, Types I and II describe heavy rainfall occurring only in a specific region, namely, either the WHRR or the EHRR. The ERA-Interim data can be used to examine the corresponding synoptic situations because the 6-hourly temporal interval of the ERA-Interim data is shorter than the duration of LDHR events ($\geq 7$ hr).

Specific heavy rainfall hours of LDHR events will be selected at 0200, 0800, 1400, and 2000 BST. For Types I and II, the heavy rainfall in the LDHR event with effective precipitation ($\geq 0.1$ mm) for at least 10 stations and heavy rainfall ($\geq 20$ mm hr$^{-1}$) for at least one station at 0200, 0800, 1400, or 2000 BST is selected for analysis. The synoptic situations during the selected heavy rainfall durations at 850 hPa are used for a synthetic analysis of the LDHR type in addition to a typical case analysis of the evolution of heavy precipitation. For Type III, the LDHR events are further classified according to the development of heavy rainfall. The typical case in each subtype is used to analyze the heavy rainfall mechanisms.

5.1. The Mechanisms of Types I and II LDHR Events

Low-level synoptic-scale weather systems, such as vortices, shear lines, troughs, and cold fronts (Ding et al., 1980), and topographic forcing play significant roles in LDHR events throughout North China. Considering the above two factors, the low-level wind at 850 hPa is employed to analyze the characteristics of weather systems and to explore the mechanism of regional heavy rainfall during LDHR events in combination with PW.

Southeasterly and southwesterly winds, representing 50.0% and 36.2% of the total heavy rainfall hours, respectively, are the two major patterns in Type I. In these two patterns, the PW near Taihang Mountain is significantly higher than that in the plains at the same latitude. In the case of the southeasterly wind
pattern, the southeasterly flow is blocked by Taihang Mountain and is then decelerated locally and deflected counterclockwise. Therefore, warm shear lines of easterly and southeasterly winds form along Taihang Mountain (Figure 5a). Heavy precipitation is observed in a narrow meridional band along Taihang Mountain (Figure 5b). In the case of the southwesterly wind pattern, cyclonic shear is found over the mountain area, in contrast to anticyclonic shear in the plain area. As a result, the decelerated southwesterly flow is deflected southward, and a warm shear line between the southerly and southwesterly is formed north of Taihang Mountain. The southwesterly wind gradually increases northward, and divergence is consequently forced on the plain. Low-level convergence appears near the mountains (Figure 5c), and a heavy precipitation belt is displayed east of Taihang Mountain to the north of 38°N (Figure 5d).

In the southeasterly case, the low-level flow collides with Taihang Mountain, which results in the deceleration and local deflection of the flow with strong ascending motion and convergence. The southeasterly flow prevails below 850 hPa at the same elevation as Taihang Mountain. The blocking effect of Taihang Mountain and the induced surface layer convergence interact with strong divergence in the upper level to produce an obvious ascent (figure omitted). Heavy precipitation is therefore observed over the slope and mountain foot in the southeasterly pattern. In the case of the southwesterly flow, however, the moist air flows along the mountain at a relatively small angle; an ascending motion is forced in the vicinity of the mountain, and strong rainfall occurs over the plain at the foot of the mountain.

Figure 4. (a–d) Total rainfall amounts (filled dots, mm) of the four types of LDHR events over C-SNC during the warm seasons of 2011–2018. The gray shading denotes topography.
The strong divergence and upper-level jet that exist at 200–300 hPa favor the development of an ascending motion at Taihang Mountain. The strong and moist southerly transports water vapor into the precipitation zone. Hence, the topographic blocking effect of Taihang Mountain plays an important role in heavy precipitation in the case of southeasterly flow. A typical case of the southeasterly pattern from 1800 BST on 12 August to 0600 BST on 13 August 2018 is taken as an example for analysis.

The overlapping between a strong divergence center to the right of the upper-level jet at 200 hPa and a strong convergence center in front of a midlevel trough significantly contributes to the heavy precipitation southeast of the area of overlap (Figure 6a). The southeasterly flow between the midlevel trough and subtropical high decelerates due to local deflection by the mountain, and a narrow convergence band is generated along the mountain (Figure 6b). Relevant quantities, including the convective available potential energy (CAPE), convective inhibition (CIN), lifting condensation level (LCL), and PW, are confirmed using the sounding data at Xingtai, which is located south of the heavy precipitation region. At 0800 BST on 12 August 2018, even though a weak CAPE (23.5 J kg\(^{-1}\)) and a moderate CIN (104.6 J kg\(^{-1}\)) are shown, the low LCL (300 m above ground level) and high PW (54 mm) provided favorable atmospheric conditions for convective initiation near Taihang Mountain. Heavy rainfall occurred when the southeasterly flow was blocked by the mountain. At 2000 BST on 12 August, the CIN was 21 J kg\(^{-1}\), and the LCL decreased to 69 m above ground level. As water vapor and energy were transported to Taihang Mountain by the southeasterly flow, the local atmosphere became conditionally unstable with a particularly large CAPE (3857 J kg\(^{-1}\)) and PW (60 mm). Notably, the stations with strong precipitation are mostly at altitudes of approximately 300 m (Figure 6b).

**Figure 5.** Composite winds and PW (green shade) at 850 hPa of the southeasterly (a) and southwesterly (c) flow patterns. A full bar is 5 m s\(^{-1}\), red lines represent shear lines, and blue solid contours denote topography (200 and 1,000 m). Total rainfall amounts (closed dots, mm) in the southeasterly (b) and southwesterly (d) patterns. The gray shading denotes topography.
The distribution of precipitation in this case is very similar to the multiyear average of precipitation in the Taihang Mountain region (Shi, 1981). The ascending branch of the secondary circulation caused by the upper-level divergence and lower-level convergence is located northwest of the heavy precipitation center, which enhances the precipitation efficiency. In the descending branch of the secondary circulation, the dry subsidence flow in the middle and lower layers is strengthened, producing weak precipitation over the CWRR (Figure 6c). An analysis of this typical case confirms the results of the synthetic analysis.

In Type II LDHR events, four typical synoptic patterns are found, that is, southeasterly flow, southwesterly flow, and the northeast shear (Shear I) and southwest shear (Shear II) of cyclonic flows, accounting for 12.4%, 23.9%, 31.4%, and 18.1%, respectively, of the total heavy rainfall hours. These typical synoptic situations are shown in Figure 7, in which Shears I and II are found in the southwestern and northeastern of
Figure 7. Composite winds and PW (green shading) at 850 hPa of the southeasterly flow (a), southwesterly flow (c), Shear I (e), and Shear II (g) patterns, in which a full bar is $5 \text{ m s}^{-1}$, red lines represent shear lines, and blue solid contours show the topography (200 and 1,000 m). Total rainfall amounts (closed dots, mm) for the southeasterly flow (b), southwesterly flow (d), Shear I (f), and Shear II (h) patterns. The gray shading denotes topography.
the C-SNC. In the plain area, the PW in Type II is larger than that in Type I. In the southeasterly pattern, weak shear of southeasterly and southwesterly winds is found over the EHRR (Figures 7a and 7b). Heavy precipitation is located in the area dominated by southeast airflow south of the shear line. There is a significant heavy precipitation center on the southwest side of Yimeng Mountain. In the southwesterly pattern, the southwesterly flow in the EHRR, which is significantly stronger than that in the WHRR, is blocked by the mountain. Obvious convergence benefits the formation of heavy precipitation in the area west of Yimeng Mountain (Figures 7c and 7d). Due to the low-pressure weather system, heavy precipitation is also observed in the northern EHRR. In the case of Shear Flows I (Figures 7e and 7f) and II (Figures 7g and 7h), heavy precipitation is located east of the shear lines, with the former in the southern EHRR and the latter in the northern EHRR. Shear Patterns I and II may be the result of the same low-pressure system at different times. An investigation shows that seven LDHR events include both synoptic situations of the Shear I and Shear II patterns. A low vortex or shear line is located south of the EHRR at the beginning of the LDHR event, and heavy precipitation appears as Shear Type I; when this heavy rainfall moves northeastward under favorable conditions, the circulation pattern is Shear Type II. All four Type II patterns show divergence at 200–300 hPa related to high-pressure systems east of 116°E and convergence associated with a low-pressure system in the lower troposphere over the EHRR. In either the southeasterly or the southwesterly circulation pattern, the prevailing southerly flow is blocked by Taihang Mountain. Ascending motion \((\leq 1.5 \times 10^{-1} \text{ Pa s}^{-1})\) is observed over the WHRR (figure omitted).
ascent in the WHRR is significantly weaker than that \((\geq 2 \times 10^{-3} \text{ Pa s}^{-1})\) produced by favorable upper- and lower-level systems in the EHRR. Ascent is detected east of the shear line, and descent occurs to the west for the Shear I and II patterns. Precipitation over the EHRR is significantly stronger than that over the WHRR. Compared to that in Type I, the vertical ascent in Type II is deeper, but the low-level convergence is weaker over the EHRR in Type II, suggesting that the topographic forcing has significant impacts on the vertical motion in addition to synoptic conditions.

A typical Type II LDHR event that occurred at 1000 BST on 13 August and 0900 BST on 15 August 2018 shall be analyzed here. In this case, heavy rainfall essentially occurred at 0000 and 2200 BST on 14 August. After turning its direction northeastward, Typhoon Yagi weakened into a depression in North China at 0200 BST on 14 August 2018. Strong shear winds appeared in a concentration region of southern North China, demonstrating a Shear I pattern (Figure 8a). At 2000 BST on 14 August, the tropical depression merged with a westerly trough (Figure 8b) and moved northeastward following the southwest airflow in front of the 500 hPa trough. The shear winds south of the low-pressure system then appeared over central North China as a Shear II pattern. Heavy precipitation occurred predominantly to the right of the low-pressure system (Figure 8c). Figure 8d shows a vertical cross along 38°N at 1400 BST on 14 August. The divergence to the right of the entrance of the upper-level jet is located east of the tropical depression. The effect of the upper divergence overlapping the lower convergence in the area northeast of the tropical depression was effective at enhancing the slantwise updraft, which is important for torrential rainfall. Convective instability is detected east of the shear line by the \(\theta_e\) field. Strong ascending motion \((\geq 12 \times 10^{-1} \text{ Pa s}^{-1})\), which is beneficial to the heavy rainfall in the east, and weak descending motion \((\geq 1.5 \times 10^{-1} \text{ Pa s}^{-1})\) to the west of the shear line are displayed. The results of this case study support the results of the synthetic analysis shown in section 3.

5.2. The Mechanism of Type III LDHR Events

Type III heavy rainfall appears in both the WHRR and the EHRR. Twenty-five of the 34 LDHR events in Type III are found in two groups (Types III_I and III_II) regarding the spatial distribution of precipitation. Figures 9a and 9b show the spatial distributions of the total rainfall of both types. Sixteen Type III_I LDHR events show heavy rainfall between 35°N and 38°N. The southwest-northeast oriented band of strong rainfall is significantly weakened in the CWRR, showing a bimodal distribution in Figure 9a. All nine Type III_II LDHR events display heavy precipitation mainly north of 38°N, which gradually increases eastward (Figure 9b).
The two peaks in Type III_1 (probably 60%) may be the result of low-pressure systems at different times. Intense precipitation occurs over the WHRR first as a direct result of the mountain blocking the prevailing airflow. However, precipitation appears over the EHRR only later, which is also produced by low-pressure systems. Hence, heavy rainfall in the WHRR and EHRR occurs at different times.

Another 40% of the heavy precipitation cases occur over both the WHRR and the EHRR in Type III_1 as a result of the zonal shear line in North China. Heavy precipitation occurs in the EHRR because of the favorable configurations of the strong upper-level divergence associated with upper-level jets and the lower-level convergence related to the shear line. In contrast, the topographic blocking of the prevailing flow to the west of the shear line near Taihang Mountain is considered to be essential for the formation of heavy rainfall in the WHRR.

In Type III_2, precipitation occurs mainly north of 38°N and increases eastward. The mesoscale low vortex or shear line associated with the topographic effect and the positive vorticity advection in front of the trough...
are the essential systems of this rainfall. A typical case that occurred at 0800 BST on 30 August and 2000 BST on 01 September 2015 is analyzed here. A westerly trough formed upstream of North China at 500 hPa, and the low-level southerly was blocked by Taihang Mountain before decelerating locally with a counterclockwise deflection, which was beneficial for cyclogenesis (Figure 10a). Local heavy rainfall occurred near the mountains (Figure 10c). With the transformation and eastward movement of the trough, the positive vorticity advection strengthened. Additionally, the cyclonic vorticity of the westerly increased after moving across Taihang Mountain (Figure 10a), while a mesoscale low vortex formed with eastward movement (Figure 10b). The precipitation increased from the WHRR to the EHRR (Figure 10d). Hence, the direction of low-level wind in the early stage is southerly in Type III_II but easterly in Type III_I.

6. Conclusions

In this study, the spatiotemporal characteristics of LDHR events are examined using quality-controlled observations with a 1 hr interval from 2,781 AWSs over C-SNC during the warm seasons of 2011–2018. Based on the data, 169 LDHR events are selected from among all the LDHR events. Composite and case analyses using ERA-Interim data are carried out to investigate the synoptic situations of the LDHR events. In addition, differences in the synoptic circulation are evaluated to indicate the causes of the different spatiotemporal characteristics of LDHR events.

The results reveal pronounced spatial variability in the frequencies and rainfall amounts of LDHR events across North China. The accumulated rainfall amount shows two peaks over the western (WHRR) and eastern (EHRR) regions of C-SNC, whereas the minimum rainfall is detected in the middle band of the CWRR; the rainfall amount therefore displays significant relationships with the topography and synoptic system. These LDHR events illustrate a higher frequency of occurrence in the EHRR than in the WHRR, which shows a clear decrease in the frequency of LDHR event occurrence from east to west.
The LDHR events present clear diurnal variations in C-SNC. The diurnal peaks in the rainfall amount, frequency, and intensity of LDHR in the WHRR and EHRR are observed during the nighttime or early morning. The diurnal variation in the rainfall amount is attributable mainly to the rainfall intensity in the WHRR and the rainfall frequency in the EHRR. The peak rainfall amount, peak frequency, and peak intensity occur during the nighttime (2100–0200 BST) in the WHRR, whereas in the EHRR, the peaks appear during the early morning (0300–0700 BST). Numerous stations display evidently smaller percentages of heavy rainfall in the nighttime than in the early morning due to the decrease in high-intensity stations. This demonstrates the different diurnal variations in heavy precipitation between the mountainous and plain regions. The systematic southeastern propagation of precipitation from the mountains to the plain partly explains the lag of the peak in the EHRR relative to the WHRR.

Analyzing 169 LDHR events and divided them into four types according to their synoptic situations and topographic effects reveals interesting results regarding the mechanisms of LDHR. Heavy rainfall occurs predominantly over the WHRR in Type I and over the EHRR in Type II. In Type III, heavy rainfall occurs in both the WHRR and the EHRR. Relatively strong rainfall is shown between the WHRR and EHRR in Type IV, but the rainfall is not comparable to that in the first three types. The representative synoptic situations for the first three types with topographic interactions facilitating the occurrence of LDHR are summarized in Figure 11.

Southeasterly and southwesterly flows interacting with Taihang Mountain are the two dominant synoptic situations in Type I. Topographic blocking of the southeasterly promotes the formation of heavy rainfall (Figure 11a), and the strong divergence and existence of an upper-level jet at 300 hPa favor the development of ascending motion near Taihang Mountain. A moist southerly is important for transporting water vapor into the precipitation zone.

Four major synoptic situations, namely, southeasterly and southwesterly flows and shear lines northeast and southwest corresponding to cyclonic flows are the key patterns in Type II (Figure 11b). Coupling between the upper- and lower-level systems gives rise to heavy rainfall in the EHRR, and the northeastward movement of shear to the northeast and southwest of the low-pressure system produces heavy rainfall east of the shear line.

Heavy rainfall is found in both the WHRR and the EHRR (but is significantly weak in the CWRR) in Type III (Figure 11c). Three mechanisms are found in this category.

First, heavy rainfall occurs initially in the WHRR due to a topographic blocking effect and then in the EHRR due to the coupling between the upper-level jet and low-level shear line. Second, the zonal shear line induces heavy rainfall simultaneously in the WHRR and EHRR. Third, the mesoscale low vortex or wind shear associated with the topographic effect and the positive vorticity advection in front of the trough lead to precipitation in the WHRR and EHRR.

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