Regimes of rainfall preceding regional rainfall events over the plain of Beijing City

Weihua Yuan1 | Hang Xu2 | Rucong Yu3 | Jian Li3 | Yingxin Zhang4 | Na He4

1LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
2LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, University of Chinese Academy of Sciences, Beijing, China
3LaSW, Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing, China
4Beijing Meteorological Observatory, Beijing, China

Correspondence
Weihua Yuan, LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China.
Email: ywh@lasg.iap.ac.cn

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Four regimes of rainfall that preceded strong regional rainfall events (RREs) over the plain area of Beijing City (BJP) were studied using hourly station-based rainfall observations during the warm season (May–October) of the past 8 years. The RREs were outlined by the maximum rainfall at all stations over the BJP each hour. The strong RREs were classified into four groups based on the rainfall that occurred in the 3 hr before the start of the events, which originated from areas northwest, southeast, northeast and southwest of the BJP. The four groups of RREs exhibited different characteristics. The number of RREs from the northwestern mountains was the highest, that is, approximately twice (four times) that from the northeastern mountains and the southwestern plain (southeastern coastal areas). The amounts, intensities and durations of the RREs from the southwestern plain were two to four-fold higher than those from the three other directions. The mean rainfall centres of the RREs from the northeast and southeast were located outside the BJP. Correspondingly, the spatial coverages and homogeneities of the RREs in the BJP from the northeast and southeast were poorer than those from the two other directions. All four groups of RREs ended to the southeast of the BJP and occurred mainly from the late afternoon to the early morning. Detailed rainfall classification based on the origination and feature analyses of all rainfall processes will enrich our knowledge of the rainfall evolutions of the BJP. In addition, combined with a study of the circulation of the rainfall processes, comprehensive understanding of finescale rainfall features will provide further information for rainfall forecasting. In the future, our analyses will be applied to the corresponding atmospheric circulations of those RREs with different origins to identify the key factors that lead to different rainfall distributions.

KEYWORDS
hourly rainfall, north china, preceding rainfall, regional rainfall events

1 | INTRODUCTION

The plain area of Beijing City (BJP) is surrounded by the Yanshan and Taihang Mountains to the north and west, with the Bohai Sea lying approximately 200 km to the east (Figure 1a). Influenced by the complex topography and multi-scale circulation systems, rainfall over the BJP exhibits obvious spatial and temporal variations. Because Beijing City is the capital and economic centre of China and is densely populated, extreme rainfall events in this region can induce urban waterlogging disasters in the city, landslides and debris flows in the mountains, and losses of human life and property. Demands for accurate weather forecasting have been voiced to improve the prediction of heavy rainfall, which requires better understanding of the features, source regions and pathways of heavy rainfall events.
The spatial distributions of the warm seasonal (May–October) rainfall over central North China are inhomogeneous (He and Zhang, 2010). In the warm season (Figure 1b), a rainfall centre is located over the BJP, and two other centres are located over the eastern coastal areas and the northeastern mountains. The rainfall amount in the warm season can account for more than 80% of the annual rainfall. Rainfall over the BJP shows variations from diurnal to inter-decadal timescales. With respect to the diurnal variations, precipitation exhibits two comparable peaks—one in the late afternoon and one in the early morning (Yu et al., 2007b; Li et al., 2008; Yin et al., 2011). Based on satellite (He and Zhang, 2010), ground-based radar (Chen et al., 2012) and rain-gauge station data (Yuan et al., 2014), the summer rainfall peaks occur gradually later along their southeasterly pathway from the afternoon (in the northernwestern mountains of the BJP) to the early evening and the early morning (over the plains and eastern coastal regions). This phenomenon is often observed downstream of elevated regions (Carbone et al., 2002). Yang et al. (2016) noted that rainfall systems that originated in the northernwestern mountains and then influenced the BJP showed the highest incidences of events among the 56 strong short-duration rainfall events that occurred from 2007 to 2014. Similarly, case studies (Sun and Shu, 2007; Wu et al., 2009) showed that rainfall over the northernwestern mountains can propagate in a southeasterly direction to the plain areas, constituting a mountain–plain rainfall process. Determining whether a mountain rainfall event remains in a local area or propagates downstream to the plains has always been a challenge for rainfall forecasting in Beijing City. Sun et al. (2018) compared the atmospheric circulations of local mountain rainfall processes and mountain–plain rainfall processes. They found that when upper cold (warm) anomalies stretched down to the lower troposphere west (east) of 110°E and when north China was situated between an upstream trough and a downstream ridge, the mountain rainfall moved to the BJP in the late afternoon and evening with the eastward progression of the circulation system.

The studies discussed above mainly focused on the propagation of rainfall systems from the northernwestern mountains. However, rainfall systems originating from other directions may also influence the BJP, and the different characteristics among the rainfall events from various sources have not yet been fully elucidated. In addition, research that focuses on rainfall events that occur over the BJP and that traces these events back to the preceding rainfall that occurs a few hours before is needed to fully understand the evolution of these rainfall processes. In this study, rainfall in the BJP was the main focus because the BJP is a rainfall centre and is densely populated, and the rainfall characteristics in the plain areas differ from those in the mountains. We defined regional rainfall events (RREs) by considering the rainfall at all stations on the BJP (following Yu et al., 2015), classified the events according to the locations of their preceding rainfall, and analysed the features of the RREs from different source regions.

The aim was to improve our knowledge of the comprehensive features and pathways of the key rainfall processes of the BJP. Moreover, because 2–12-hr rainfall forecasting remains the bottleneck in rainfall forecasting operations, analysis of the rainfall that occurs a few hours before the rainstorms in the BJP will also be helpful for forecasting rainfall in this region.

Following this introduction, the data and methods are described in section 2. The mean characteristics of the RREs during the warm season are described in section 3. The four regimes of the preceding rainfall of the strong RREs are presented in section 4. Finally, a discussion and summary are presented in section 5.

2 | DATA AND METHODS

Hourly rainfall data from 971 rain gauges covering north China in the warm seasons of 2009–2016 were used in this study (Figure 1a). This data set was collected and quality controlled by the National Meteorological Information Center of the China Meteorological Administration. The quality testing consisted of a climatological limit value test, a station extreme value test and an internal consistency test. All stations were missing fewer than 25% of the hourly observations in the warm seasons of 2009–2016. The threshold of the hourly rainfall amount was 0.1 mm/hr.

The RREs were defined based on the hourly rainfall records from 69 stations on the BJP (red dots in the black rectangle of Figure 1a), following the example of Yu et al. (2015). To determine the hourly rainfall amount at all 69 stations at hour t ($P_t (i = 1, 69)$), the maximum record of all stations was found ($P_{x, t}$), and the time series of $P_{x, t}$ were then used to represent the rainfall intensities at hour t over the whole BJP. In Figure 2, the dots with different colours represent $P_{x, t}$, and the black line represents $P_{x, t}$. Based on the time series of $P_{x, t}$, the RREs were classified according to their durations without any dry period or with a maximum 1-hr dry period during a single rainfall event (Yu et al., 2007a).

A regional rainfall coefficient (RRC) was calculated following the work of Yu et al. (2015) to quantify the rainfall temporal variability in space,

$$\text{RRC} = \frac{2 \times P_{\text{mean}}/P_{\text{max}} + P_{\text{min}}}{(\overline{P_{\text{max}}} - \overline{P_{\text{min}}})} \times [(N - 1)/(N - 1)] \times 100\%,$$

where $N$ ($N_0$) is the total number of stations (rainy stations), and $P_{\text{mean}}$, $P_{\text{max}}$, and $P_{\text{min}}$ are the mean, maximum and minimum rainfall amounts, respectively, observed at all rainy stations.

We performed empirical orthogonal function (EOF) analyses of the rainfall that occurred within 3 hr before the beginning of an RRE. The leading first four modes featured large value centres to the northwest, southeast, northeast and southwest of the BJP. Based on the principal components of the first four modes of EOF analyses and the spatial correlation analyses, the RREs were classified into four groups. The detailed classification methods are described in section 4.
3 | CHARACTERISTICS OF REGIONAL RAINFALL EVENTS

The spatial distributions of the rainfall events over central North China were inhomogeneous in the warm season. Figure 1b illustrates the rainfall amounts during the warm season. Large rainfall centres were located in front of the northeastern mountains of the BJP and in the southeastern coastal regions. The BJP was also covered by a rainfall centre, and the mean rainfall amount in this area (2.1 mm/day) was greater than that at 91% of the stations in the central region of north China.

In the study conducted by Yu et al. (2015), rainfall at eight national stations on the BJP was used to define the RREs. Here, using a similar method, the rainfall from 69 national and automatic stations was applied to identify the RREs. Taking 0.1 mm/hr as the threshold for measurable rainfall, 1888 RREs were selected during the eight warm seasons. The distributions of the number of events, mean intensities, durations, and RRCs are presented as functions of the maximum hourly intensities of the RREs in Figure 3. More than 900 RREs had maximum intensities less than 1 mm/hr (Figure 3a), mostly lasting for...
few hours (Figure 3b) and occurring at a few stations (Figure 3c). When the maximum intensity of the RREs was greater than 1 mm/hr, the number of events rapidly decreased, and the mean intensity, duration, and RRC of the RREs sharply increased. When the maximum intensity was greater than or equal to 5 mm/hr, the rainfall frequency that accumulated in each bin over the previous eight warm seasons declined to less than 100. In addition, the duration and mean intensity increased gradually. The mean intensities, durations and RRCs of the RREs all reached their maxima when the maximum intensity was 20–30 mm/hr. The total number of RREs with maximum intensities greater than 30 mm/hr was relatively low, with 99 events observed over the previous eight warm seasons. Their mean duration and RRC were 9.8 hr and 43%, respectively, which were greater than those of the rainfall events with a maximum intensity of 10–20 mm/hr (6.8 hr and 32%) and lower than those events with a maximum intensity of 20–30 mm/hr (11.5 hr and 47%).

Figure 4 shows the evolution and the RRC of the RREs that lasted more than 6 hr. The mean evolution of the events was represented by the ratios of the rainfall frequencies before (negative hours) and after (positive hours) the peaks of the events relative to that at the peak time (hour 0). Similar to the results of Yu et al. (2013; 2015), the evolution of the long-duration RREs was asymmetric, such that the frequency before the peak was smaller than that after the peak. The time of the RREs, measured from the start to the peak of the event, was usually shorter than that between the peak and end, and the frequency could persist at a high level for a longer period towards the end of the event. The peak of the RRC was later than that of the frequency, indicating that most RREs were uniformly spread across more stations after reaching the peak. The above results were based on data from 69 stations on the BJP, further confirming the results of Yu et al. (2015) (which were based on eight stations) and verifying the reliability of this method.

To avoid the effects of the immense local low-impact RREs with weak intensities and short durations, we hereafter only focus on the 464 strong RREs with an hourly intensity threshold of 5 mm/hr. Figure 5a presents the spatial distribution of rainfall amounts at all stations where strong RREs occurred. During strong RRE hours, the rainfall was concentrated around the BJP and was distributed along a southwest–northeast direction. More than 70% of the total warm season rainfall fell during strong RREs at 210 stations (black dots in Figure 5b). In the BJP, the rainfall amounts during strong RREs can account for more than 90% of the total rainfall in the warm season. As a result, focusing on the rainfall in the BJP, the major concern should be the evolutions of strong RREs and the distributions and developments of the rainfall that occurred a few hours before the start of the strong RREs.

Figure 6 shows the spatial distributions of the rainfall amounts during the 3 hr before the start (Figure 6a), from the start to the peak (Figure 6b), from the peak to the end (Figure 6c), and 3 hr after the end of the strong RREs (Figure 6d). In the 3 hr before the start of RREs (Figure 6a),

![FIGURE 4](image-url)  
**FIGURE 4** The ratio (%) of the composed frequency (line with circles; left y-axis) before (−) and after (+) the rainfall peak relative to the frequency at the peak time (time zero) and the corresponding evolution of the RRC (dashed line with triangles; right y-axis) for RREs that lasted longer than 6 hr.

![FIGURE 5](image-url)  
**FIGURE 5** (a) Mean rainfall amounts (units: mm/day) when strong RREs occurred. (b) Ratio of rainfall amounts when the strong RREs occurred relative to the rainfall amounts in the warm seasons. The dots represent the stations where the strong RREs accounted for more than 70% of the total rainfall amount. [Colour figure can be viewed at wileyonlinelibrary.com]
the rainfall mainly occurred in the northwestern mountains. In addition, large rainfall centres were also observed in the northeastern mountains and in the southwestern and southeastern plains. During the start and peak of the strong RREs (Figure 6b), the rainfall in the BJP was greatly strengthened. The rainfall maximum was located in front of the western mountains of the BJP, and the area with the larger rainfall amount was presented as a belt in a southwest–northeast direction. Between the peak and end of the RREs (Figure 6c), the rainfall centres were located to the east and south of the BJP, and the rainfall intensity in the BJP weakened. In the 3 hr after the end of the RREs (Figure 6d), the rainfall mainly occurred in Tianjin and the adjacent regions. A summary of the above results indicates that the northwestern mountains experienced the most rainfall preceding the strong RREs over the BJP. However, before the start of the RREs over the BJP, rainfall also appeared in the northeastern mountains and the southwestern and southeastern plains, and the rainfall over the southeastern region of the BJP was usually treated as the downstream rainfall of the BJP before. In the following section, the regimes of the rainfall preceding the strong RREs and the features of the RREs with different source regions are analysed.

4 | FOUR REGIMES OF THE RAINFALL PRECEDING THE STRONG RRES

To identify the dominant regimes of the rainfall preceding the RREs in the BJP, EOF analysis was performed on the rainfall that occurred 3 hr before the strong RREs, and four leading modes were found. Then, typical RREs of the four regimes were selected based on EOF and correlation analyses. In addition, the hourly evolution of the rainfall before the start of the four groups of the selected RREs was examined to verify that the selected RREs originated from four different directions outside the BJP and finally moved to the BJP.

The spatial distributions of the first four modes are shown in Figure 7. The percentages of the variances
accounted for by the first four eigenvalues of the EOF analysis were 13.4, 11.9, 7.1 and 5.9%. These percentages were all statistically significant according to North et al. (1982). The first EOF mode featured a positive monopole pattern centred near 40°-41°N, 115°-116°E, which represented the rainfall systems originating in the northwestern mountains (Figure 7a). The second (third) EOF mode featured a positive southeast–northwest (northeast–southwest) dipole mode, with a positive centre located in the southeastern (northeastern) region of central north China (Figure 7b,c). In the fourth mode, the positive patterns were located in the northeastern and southwestern corners of central north China (Figure 7d), and the centre in the southwest was stronger. The spatial distribution of the first four modes was generally consistent with the rainfall preceding the RREs in Figure 6.

Based on the EOF and correlation analyses, typical RREs from the four directions were selected. First, the cases with principal components larger than one standard deviation in the first four modes were selected and their mean states were calculated. In this step, 55, 38, 31 and 24 cases were chosen for the groups 1–4 (148 cases in total). Second, the correlation coefficients of the spatial distributions of the preceding rainfall amounts between the remaining 316 cases and the mean states of the four groups were calculated. If the correlation coefficient was greater than 0.30, the case was assigned to that group. If any case had high correlation coefficients with the mean states of more than one group, the case was assigned to the group with the highest correlation coefficient. Third, to ensure the rainfall processes originated from only one direction, cases with rainfall in two or more directions in the 3 hr before the RREs of the BJP were excluded. Following the above three steps, 209 cases were selected, and the number of events in each group is listed in Figure 8a. To verify the reliability of the classification, clustering analyses based on the spatial correlations were also applied to the average rainfall in the 3 hr before the start of the RREs. The rainfall distribution of the first four clusters was similar to that in the EOF analyses (figure omitted). The distributions of the rainfall amount in the 3 hr before the start, from the start to the peak, from the peak to the end,
and in 3 hr after the end of the RREs of the four groups are shown in Figure 9. Rainfall from four directions occurred outside the BJP before the start of the RREs and then moved to the BJP. Moreover, the evolution of rainfall in each hour from three to zero hours before the start of the RREs and the detailed movements of rainfall processes from the four directions to the BJP are shown in Figure 10.

The four groups of strong RREs presented different characteristics. The groups originated in different ways, and four regimes for the preceding rainfall were identified. The preceding precipitation originated from the northwest, south-east, northeast and southwest of the BJP. The number of events in each group was different (Figure 8a). Ninety-five strong RREs had origins in the northwestern mountains, which accounted for the largest number overall. The number of RREs from the southeast was the lowest (26 events), and the numbers for the southwesterly and northeasterly directions were similar (48 and 41 events). In the 3 hr before the start of strong RREs (the first column in Figure 9), the rainfall distributions of the first three groups (Figure 9a,e,i) closely resembled those in the first three leading EOF modes (Figure 7a,c); the correlation coefficients were 0.89, 0.9 and 0.9, respectively. In the fourth group (Figure 9m), the rainfall mainly originated southwest of the BJP, and the weaker rainfall centre over the northeast of the BJP in the fourth EOF component was not apparent, which matched the principles of the case selection.

Compared with the rainfall before the start of the RREs, the intensities of the overall rainfall processes strengthened in the early stages of the RREs (from the start to the peak; see the second column in Figure 9), except in group 2. In the second group, the maximum rainfall amount at a single
station occurred in the 3 hr before the strong RREs in Tianjin (Figure 9e). During the early stages of the RREs, the rainfall amounts over the entire BJP notably increased, and the rainfall centres were usually located along the northwestern (groups 1, 2 and 4) and northeastern (group 3) mountains. In group 3 (Figure 9j), the major rainfall centre was located outside the BJP, and the BJP was located at the margin of the rainfall systems. Correspondingly, the RRC of the RREs in group 3 was small. In the later stages of the RREs (from the peak to the end, as shown in the third column in Figure 9), the rainfall systems moved southeastwards in all four groups, with the rainfall centres located to the eastern and southern areas of the BJP. In the 3 hr after the rainfall events (the fourth column in Figure 9), the rainfall processes weakened and moved further to the southeast, mainly over Tianjin City and to its north. In all four groups, regardless of where the rainfall systems originated, they all ended southeast of the BJP.

**FIGURE 9** As in Figure 6, but for the rainfall of groups 1–4 (first–fourth rows; units: mm/hr) in the four periods (first–fourth columns) [Colour figure can be viewed at wileyonlinelibrary.com]
In each group, the ratios of the events lasting for 1–6 hr (short duration) to those lasting more than 6 hr (long duration) were different. For the rainfall events originating northeast of the BJP (group 3), almost seven-eighths of the events were of short duration. Moreover, the durations of the long-duration rainfall events from the northeast were short, lasting only approximately 9 hr (Figure 8d). As a result, the mean duration of the strong RREs in group 3 was less than that of any other group, and the mean rainfall amount and intensity for the long-duration RREs were the weakest (Figure 8b,c). This result is consistent with Figure 9, insofar as the majority of the rainfall in this group did not occur over the BJP. For the events originating from the northwest (group 1) and southeast (group 2), the number of occurrences of short-duration rainfall events was approximately three times the number of long-duration events. However, the mean rainfall amount of the short- and long-duration rainfall events in group 2 was only half of that in group
due to the weaker intensities and shorter durations of the long- and short-duration rainfall events in group 2.

The rainfall from the southwest (group 4) was distinct from the other directions. The occurrences of long-duration rainfall events were similar to those of short-duration events (Figure 8a). The mean duration of the 18 long-duration rainfall events was almost 12 hr. Among the 18 long-duration RREs, 16 events lasted longer than 10 hr, and three events lasted longer than 20 hr. In the other three groups, only one event lasted longer than 20 hr (in group 1). The two extreme torrential rainfall events on June 20, 2016 and June 21, 2011 both originated southwest of the BJP, which led to huge rainfall amounts over Beijing City. The RRE on June 20, 2016 lasted for 35 hr, which was the longest RRE during the 2009–2016 period. In addition, the mean hourly intensity of the long-duration RREs in group 4 was 3.88 mm/hr, which was considerably stronger than that in any other groups (less than 1 mm/hr). Due to the long durations and heavy intensities of the RREs in group 4, the mean rainfall amount was 2–4 times greater than that of the other groups. Furthermore, the coverages and homogeneities of the RREs of group 4 were the greatest (Figure 8e).

The occurrences of the RREs of the four regimes presented different diurnal variations (Figure 11). Among the four groups, the occurrences of the rainfall events were more common in the late afternoon to the early morning, and the occurrences of the peaks during this period were almost double those of other times. The RREs from the northwestern mountains mainly occurred from 1900 to 0200 Local Solar Time (LST, UTC+8), and the minimum occurred at noon (Figure 11a). The peak frequencies of the RREs of group 2 (Figure 11b) and group 4 (Figure 11d) appeared from 0300–0600 LST, which was later than that of group 1. The occurrences of the rainfall in group 3 remained at a higher level from 1500–0600 LST (Figure 11c). The ratio of the rainfall frequency from 1500–1800 LST relative to the total was the highest in group 3.

5 CONCLUSIONS AND DISCUSSION

By analysing the spatial distributions of the rainfall preceding strong RREs over the BJP in eight recent warm seasons, four regimes of the preceding rainfall located in the northwest, southeast, northeast and southwest of the BJP were identified. Nearly one-half of the strong RREs moved from the northwestern mountains, while the number of events from the northeast and southwest were similar (~21%) and the events from the southeastern plain accounted for only 12% of the total of all four groups. The mean rainfall amount, hourly intensity and duration of the events from the southwest were 2–4 times those of the other regimes. The intensities of the rainfall processes from the northeast and southeast were generally weaker, and these rainfall coverages were smaller than the others. This occurred because the rainfall centres of these events were usually located outside the BJP, and these rainfall systems barely impacted the BJP. The RREs from the four regimes usually peaked during the late afternoon to early morning, and the peaks of the rainfall events from the southeast and southwest occurred later than those from the northwest. All four groups of events, irrespective of where they originated, moved southeast as they dissipated.

FIGURE 11  Mean diurnal cycle of the rainfall frequencies of the RREs for all events in groups 1–4 (a–d, respectively). The x-axis is the LST.
The four regimes of the preceding rainfall events for the BJP further confirm the highest incidences of the rainfall processes originating in the northwestern mountains. However, the southeastern plain of the BJP, which is mainly considered as the downstream region, could also be an area of origin for the rainfall processes influencing Beijing City, and this was emphasized in this study. The different characteristics of the rainfall associated with the four regimes, such as their intensities and durations, indicate different atmospheric conditions during the formation of the rainfall events. Primary analysis showed that the temperature anomalies in the upper level presented different spatial and vertical patterns, and further complementary studies will be completed in the future. Based on the fine-scale rainfall classifications and the detailed rainfall feature analyses, as well as the study of the circulations of the preceding rainfall events, knowledge of the evolution of events will be enriched. In the present weather forecasting operations, even with the developments and applications of numerical models and data assimilation techniques, 2–12-h rainfall forecasting remains difficult. A comprehensive understanding of the evolution of rainfall processes will provide more information for 2–12-h rainfall forecasting. In the future, more analyses will be conducted on the atmospheric circulations of the RREs of different origins to identify the key features that lead to different rainfall distributions.

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ORCID

Weihua Yuan http://orcid.org/0000-0001-7104-0331
Rucong Yu http://orcid.org/0000-0001-6297-1185
Jian Li http://orcid.org/0000-0001-7223-0022

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