Comparison of Heavy Rainfall Events Originated from Different Directions of Beijing City

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ABSTRACT

Strong rainfall events originated from the northeast (NE) and southwest (SW) directions of the plain area of Beijing City (BJP) over 8 recent warm seasons (May–September of 2009–2016) were analyzed by using hourly merged rainfall, satellite brightness temperature, and the fifth-generation ECMWF reanalysis (ERA5) data. Such heavy regional rainfall events (RREs) with different origins present quite different features in both the precipitation itself and its corresponding circulations. The heavy RREs originated from the SW occur more frequently in the flood season of North China (July and August), and the peak time of rainfall occurrences is in the early morning. They are linked with stronger large-scale circulation forcing, compared with the NE-originated events. Meanwhile, the ratio of heavy rainfall to the total rainfall in SW-originated events, the mean spatial coverage of rainfall, and associated convective index, are also larger, for the SW events. The heavy RREs from the NE occur more frequently in June and July (before the traditional flood season), with a more apparent afternoon peak. They exhibit stronger convective features, with higher maximum convective index values, but the large-scale forcing is weaker at the hour of onset. These features of the RREs from different directions of Beijing City and associated precursor circulation signals help better forecast RREs over the BJP.

Key words: heavy rainfall, hourly rainfall features, rainfall with different origins

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1. Introduction

Precipitation is a meteorological phenomenon that has attracted much attention from scientists and the public, especially with respect to rainfall in large cities (Sun and Shu, 2007; Wu et al., 2009; Chen et al., 2011). Beijing City is the capital of China and is densely populated. Extreme rainfall in this region can induce urban waterlogging disasters in the city, landslides and debris flows in the mountainous areas, and losses of human life and property (Sun et al., 2012; Zhong et al., 2015). As a result, many studies have focused on the rainfall features around Beijing from diurnal to decadal timescales (Li et al., 2008; Yin et al., 2009; He and Zhang, 2010; Chen et al., 2012; Yu et al., 2014; Yuan et al., 2014).

The topography and underlying surface of central North China are complex. The plain area of Beijing City (BJP) is surrounded by the Yanshan and Taihangshan mountains, with the Bohai Sea lying to the east (Fig. 1). Influenced by the complex topography and air circulations at different spatiotemporal scales (Tao, 1980; Yuan et al., 2014), the summer rainfall over central North China is quite inhomogeneous (He and Zhang, 2010; Yuan et al., 2014). A greater amount and intensity of rainfall are found over the southeastern plain and coastal area, while the frequency of rain is greater over the middle of the conjunction area between the mountains and plains (Yuan et al., 2014). Rainfall shows an obvious northwest (NW)–southeast (SE) oriented propagation over central North China (Yin et al., 2011), where the late-afternoon peaks were found over the mountains, the midnight peaks over the BJP, and early-morning
peaks over the coastal areas. Similar delayed diurnal rainfall features also exist along the eastern periphery of the Tibetan Plateau (Chen et al., 2010; Bao et al., 2011) and the Great Plains in the United States (Carbone et al., 2002).

Apart from the heavy-rainfall producing storms from the northwestern mountains, statistical analysis (Yang et al., 2016) has also highlighted the storms from the north and south, which are influenced by different large-scale synoptic circulations. Yuan et al. (2018) selected 209 strong regional rainfall events (RREs) in the warm seasons (May–September) during 2008–2016 and grouped them based on their origins. The RREs were originally defined by Yu et al. (2015) according to the rainfall recorded by all stations in the BJP to describe the spatiotemporal variations in rainfall in that region. In Yuan et al. (2018), most strong RREs (94) were found to derive from the area NW of the BJP. Because rainfall systems from the NW usually affect the BJP, researchers have fully analyzed the features and circulation background of the rainfall events propagating from that direction (Yang et al., 2016; Sun et al., 2018). However, nearly half of all rainfall events were from the northeast (NE; 48) and southwest (SW; 41), which also brought substantial amounts of rain to the BJP. Yuan et al. (2018) pointed out that, although the occurrences of RREs from the NE and SW are comparable, the intensity and duration of the SW-originated rainfall events are much greater than those from the NE. However, the circulations associated with RREs from the NE and SW have not been thoroughly analyzed and compared.

The formation of heavy rainfall is associated with large-scale and local thermal and dynamical factors. For example, the low- and upper-level jet streams are important for large-scale vertical upward motion and water vapor transport (Shinoda et al., 2005; Luo et al., 2016; Du and Chen, 2019). Over the BJP, an obvious positive feedback was found between the local heavy rain and the appearance of boundary layer jets (Sun, 2005). Over the Great Plains of the United States, the low-level jet was extremely important to heavy rainfall (Higgins et al., 1997). The low-level jet not only transports water vapor to the rainy center (Findlater, 1969; Saulo et al., 2007), but also triggers mesoscale disturbances due to the vertical wind shear below the jet core (Kuo and Seitter, 1985; Limaitre and Brovelli, 1990). Heavy rainfall usually occurs to the south of the entrance region of the upper troposphere jets due to the upper-level divergence (Shin and Lee, 2005). The hourly rainfall features and the corresponding atmospheric circulations of the NE- and SW-originated RREs also need to be analyzed in detail. Analyses of the large-scale and local thermal and dynamical factors, as well as a comprehensive study of the rainfall features, would be helpful in understanding the properties of rainfall events from different directions over the BJP.

In this study, we use the definition of RREs and their origins from Yuan et al. (2018) and analyze the features of the RRE events from the NE and SW in detail, based on the gauge-satellite merged rainfall data and brightness temperature data from the Fengyun (FY) satellites. Additionally, the atmospheric circulation backgrounds are compared to help us understand the differences in rainfall features between the NE- and SW-originated RRE events. The aim of this study is to improve knowledge on the features of rainfall events from different directions of Beijing City and the associated precursor circulation signals, and to help better forecast RREs over the BJP. The data and methods are described in Section 2. The rainfall characteristics of the RREs from different directions and their corresponding circulations are described in detail in Section 3. Finally, a summary and discussion are given in Section 4.

2. Data and methods

2.1 Data

The hourly merged precipitation analysis product over China (CMPA; Shen et al., 2014) for the period 2009–2016 is used. The data are provided by the National Met-
eorological Information Center of the China Meteorological Administration (CMA). The CMPA merges high-density hourly data from more than 30,000 automatic weather stations over China with the US Climate Prediction Center morphing technique (CMORPH) precipitation product by using the improved probability density function and optimal interpolation (PDF–OI) merging algorithm. The spatial resolution is 0.1° × 0.1°. A report on the overall quality of CMPA-Hourly and its cross-validation results with station records can be found in Shen et al. (2014). Also, a large number of studies have used this dataset to analyze rainfall features over China (Gao et al., 2019; He et al., 2019).

To analyze the convection-related features associated with rainfall events, the blackbody brightness temperature (TBB) is used. TBB is derived from the first infrared channel of the FY geostationary satellites from 2009 to 2016 (with a wavelength of 10.3–11.3 μm). The data are archived by the CMA and are devoted to cloud observation in South and East Asia. The dataset covers the same region as the scanned area of the satellite with a precision of 1 K. The TBB product is averaged over 0.1° × 0.1° grids and is calibrated and released by the National Satellite Meteorological Center of the CMA. To compare the convective activity related to the rainfall events over the BJP, the cloud classification (CLC) products during the same periods are also analyzed, prior to the subsequent main analyses (Rossow and Schiffer, 1999; Yang et al., 2008; Liu et al., 2009). Introductions to the TBB and CLC data can be found at http://satellite.nsmc.org.cn/PortalSite/Data/Satellite.aspx.

To analyze the precursor circulation signals associated with the NE- and SW-originated rainfall events, in this study, the atmospheric circulation corresponding to the heavy RREs is examined by use of the reanalysis data one hour before the onset of heavy rainfall. Using the circulation ahead of the RREs, instead of during the events, is intended to reduce the effects of feedback of the rainfall on the circulation. The latest hourly fifth-generation ECMWF reanalysis (ERA5), which is supervised by the ECMWF and developed through the Copernicus Climate Change Service, is used (Hersbach and Dee, 2016; Hersbach et al., 2019). The ERA5 dataset used in this study has a horizontal resolution of 0.25° × 0.25° and contains 37 vertical levels. The variables of wind, specific humidity, vertical velocity (ω), and the convective available potential energy (CAPE) are used.

2.2 Methods

The RREs in Yuan et al. (2018) are defined based on the hourly maximum rainfall records at 69 stations over the BJP (the area outlined by the black rectangle in Fig. 1); the elevations of all 69 stations are below 100 m. For each hour, t, the maximum precipitation is defined as \( P_{x,t} = \max(P_{i,t}) \) (i = 1, 2, ..., 69), where \( P_{i,t} \) is the measurable rainfall \( (\geq 0.1 \text{ mm h}^{-1}) \) at the \( t \)th station. The time series of \( P_{x,t} \) are then used to represent the rainfall intensity at hour \( T \) over the BJP. The occurrence time of strong RREs (maximum hourly intensity \( \geq 9 \text{ mm h}^{-1} \)) and their origins in Yuan et al. (2018) are used. A rainy hour is defined as one in which more than or equal to 0.1 mm of precipitation is accumulated during this period of 1 h. The average values of hourly mean rainfall amount (accumulated rainfall), frequency (the ratio of observational hours with measurable precipitation), and intensity (the mean rate in rainy hours) are calculated for each RRE. The spatial distributions of rainfall amount for the events originated from the NE and SW identified based on the CMPA data (Fig. 2) are compared with the results of the station rain gauge data [Fig. 9 in Yuan et al. (2018)]. Generally, the rainfall systems presented by the merged rainfall data are similar to those revealed in Yuan et al. (2018), which further demonstrates the reliability of the CMPA data.

Based on the masked TBB data (grid cells without clouds are removed) in the cloudy grid (based on CLC), the convective index (\( I_c \)) is calculated by using the method proposed by Nitta and Sekine (1994), which is expressed as:

\[
I_c = \begin{cases} 
243 - \text{TBB} & \text{(TBB < 243 K)} \\
0 & \text{(TBB \geq 243 K)} 
\end{cases}
\]

For each region, the following exponential function [Eq. (2)] is used to fit the rainfall intensity–amount distribution, in which \( I_r \) represents the hourly rainfall intensity and \( \Pr(I_r) \) is the accumulated rainfall amount (Li and Yu, 2014). Please see subsection 3.1 for more details on how to obtain Eq. (2). The parameters \( \alpha \) and \( \beta \) are determined by the least-squares fitting of Eq. (2). The linear-form Eq. (3) is derived by taking the natural logarithm of both sides of Eq. (2).

\[
\Pr(I_r) + 1 = \exp(\alpha - I_r/\beta), \quad (2) \\
\ln[\Pr(I_r) + 1] = \alpha - I_r/\beta. \quad (3)
\]

The two parameters modulate different parts of the fitted line: \( \alpha \) is more closely related to the weak precipitation amount, and \( \beta \) is usually used to assess the amount of strong rainfall (Li and Yu, 2014).

3. Results

3.1 Rainfall features

Figure 3 illustrates the occurrence of rainfall events from the NE and SW of the BJP during each month of
May–September. The two types of rainfall events rarely occur in May, and only one (two) event(s) is (are) found from the NE (SW), respectively. The events from both directions occur more frequently in July. The rainfall events from the NE mainly occur in the early part of the summer (June to July), while events from the SW occur more frequently in the later part (July and August).

Over North China, rainfall events lasting for one to six hours (short duration) and those lasting more than six hours (long duration) reach an hourly maximum at different times (Yuan et al., 2014). The late-afternoon peak of short-duration rainfall events may be explained by the diurnal variation of low-level atmospheric stability caused by solar heating, and the early-morning peaks of long-duration rainfall are usually linked to large-scale circulations (Chen et al., 2010; Yuan et al., 2010). Regarding the long- and short-duration rainfall events (Figs. 3c–f), the number of short-duration RREs from the NE constitutes the majority of all RREs, while the numbers of short- and long-duration RREs from the SW are comparable. For both short- and long-duration events, RREs from the NE occur more frequently in June and July (Figs. 3c, e). Except for one event in August, the long-duration events from the NE all occur in June and July (Fig. 3e). RREs from the SW occur in every month from May to September, and the number of long-duration events is the largest in July (Figs. 3b, f). According to Ding and Chan (2005), late July and early August comprise the traditional flood season in North China, thus the rainfall is usually longer in duration in these months (Yuan et al., 2010). As indicated in Fig. 3, the rainfall in this traditional flood season of central North China mainly derives from the SW.

All the hourly rainfall intensity values for the two RRE types for the period 2009–2016 are binned into 1 mm h$^{-1}$ increments. The distributions of rainfall amount with hourly intensity (shown in Fig. 4) approximately follow a pattern of exponential decay. The logarithm of the rainfall amount decreases linearly. Parameters $\alpha$ and $\beta$ in Eq. (2) can be determined by using the least-squares method and the linear function described by Eq. (3). The values of parameter $\alpha$ for RREs from the NE and SW are 5.76 and 6.38, respectively, whilst the values of $\beta$ are 10.52 and 15.81 mm h$^{-1}$ (Table 1). According to Li and Yu (2014), the two parameters modulate different parts of the fitted line: $\alpha$ is more closely related to the weak precipitation amount, whilst $\beta$ is usually used to assess the amount of strong rainfall. Therefore, the position on an $\alpha$–$\beta$ plane can explicitly represent the key characteristic of the amount–intensity structure of precipitation. As shown in Table 1, weak rainfall occupies a large portion of the total rainfall of the RREs from the NE. The value of $\beta$ is higher in rainfall events from the SW, indicating a large percentage of the total strong rainfall amount.

Figure 5 shows the normalized (by the daily mean) di-

Fig. 2. Distributions of the rainfall rate (mm h$^{-1}$) from the hourly merged precipitation analysis product over China (CMPA) for strong regional rainfall events (RREs) from the (a–d) northeast (NE) and (e–h) southwest (SW) directions of the plain area of Beijing City (BJP). Periods shown are (a, c) three hours before the start of the events, (b, f) between the start and the peak, (c, g) between the peak and the end, and (d, h) three hours after the events. The white boxes outline the BJP.
The major diurnal peak of rainfall amount from the NE-originated RREs is at midnight (Fig. 5a), with two comparable weaker peaks appearing during the late afternoon (1600 local standard time (LST)) and early morning (0500 LST). The diurnal amplitude of rainfall amount for the SW-originated RREs is weaker, reaching a relatively high value during late evening. For rainfall frequency, the diurnal curves are re-

**Fig. 3.** The number of monthly occurrences of strong RREs from the (a, c, e) NE, and (b, d, f) SW directions of the BJP. (a, b) Total number, (c, d) short-duration events, and (e, f) long-duration events.

**Fig. 4.** The accumulated rainfall amount (mm) binned by hourly rainfall intensity (black dots) and its exponential distribution fit line (black curve) for strong RREs from the (a) NE and (b) SW of the BJP. The blue squares and blue lines are the logarithm of the rainfall amount. The $e$-folding of the exponential distribution is marked by the red dashed vertical lines.
relatively smooth, with fewer peaks (Fig. 5b). Compared with Fig. 5a, an obvious difference is that the major peak in the rainfall frequency occurs later than the major peak in the amount. The peak of rainfall frequency for the SW-originated events occurs in the early morning. Regarding rainfall intensity (Fig. 5c), for the NE-originated RREs, the peak is earlier than that of the rainfall amount (Fig. 5a). For the SW-originated events, the diurnal cycles of rainfall frequency and intensity are nearly out of phase.

3.2 Circulations

In addition to the rainfall features, convective features and large-scale circulation backgrounds associated with RREs from the NE and SW of the BJP are analyzed. Figure 6 shows the convective features revealed by the convective index observed by the FY satellites. Generally, the rainy regions in Fig. 2 correspond well to the areas of high $I_c$ values. The regions with high $I_c$ values migrate from different directions to the BJP, and then retreat southeasterly. During all the processes of the two types of rainfall systems, the highest $I_c$ values appear outside the BJP. For the RREs from the NE, the areas with an $I_c$ value greater than 7 are narrow and oriented in almost the east–west direction, with higher center values (Fig. 6c). For the RREs from the SW, the coverage of $I_c$ values higher than 7 is larger, and this area shows an apparent SW–NE orientation (Fig. 6g).

The air circulations at the hours of onset of the two types of RREs are shown in Figs. 7–9. For the RREs from the NE and SW, the BJP is dominated by southwesterly and southerly lower troposphere flows, respectively. The regional average wind speed is 2.32 m s$^{-1}$ and about 4.82 m s$^{-1}$ at 850 hPa (Fig. 7). For the RREs from the NE, the averaged low-level winds are less organized (Fig. 7a). For the RREs from the SW, the mean wind speed is greater, and the wind directions are more consistent over the BJP (Fig. 7b). The spatial distribution of low-level southerly flow (stronger in the south of the BJP and weaker in the north) and the mountains to the north of the BJP result in large ranges of convergence and upward motion (Fig. 8b). At the upper level, the westerly over the north of the BJP is strengthened and the maximum wind belt moves northward in the SW-originated events (Fig. 7b), when compared with the NE-originated events. The BJP is to the south of the jet core and the spatial distribution of upper-level zonal winds in the SW-originated events also favors strong uplifts. In the NE-originated events, the upper-level jet core is located to the south and the BJP is to the north of the entrance region of the upper troposphere jet (Fig. 7a). One hour before the onset of the NE-originated events, spatial distribution of the upward motion near the BJP is in disorder and both positive (downward motion) and negative (upward motion) centers are closely located (Fig. 8a). However, for the SW-originated events, a large area of strong upward motion in the lower troposphere can be found over the southern boundary of the BJP (Fig. 8b). Meanwhile, the strong low-level southerly can bring more water vapor to the BJP, which is consistent with the much greater quantity of precipitable water (vertically integrated specific humidity) in the SW-originated events (Fig. 9b). The spatial coverage of large vertically integrated specific humidity (greater than 45 kg m$^{-2}$) is also

|   | $\alpha$ | $\beta$ |
|---|---------|---------|
| NE | 4.76    | 11.32   |
| SW | 6.18    | 16.11   |
larger in the SW-originated events than in the NE-originated events, which is consistent with the distribution features of rainfall and convective index.

4. Conclusions and discussion

By analyzing hourly merged rainfall, satellite brightness temperature, and ERA5 reanalysis data for strong RREs from the NE and SW of the BJP during eight recent warm seasons, the features of strong RREs over the BJP have been revealed in detail, as summarized below.

(1) Regional rainfall events (RREs) from the northeast (NE) of Beijing City occur mainly in June and July, and those from the southwest (SW) occur more fre-
The rainfall intensity is stronger and the ratio of heavy rainfall amount to the total is larger in the RREs from the SW than those from the NE. The diurnal cycles of the two rainfall types are also different. The afternoon peak is more apparent in the NE-originated RREs, especially for the rainfall amount and frequency. For the SW-originated RREs, the rainfall frequency peak appears in the early morning, later than that in the NE-originated events RREs.

(2) The coverage of high values of the convective index ($I_c$) for the SW-originated RREs is large. However, a stronger maximum $I_c$ appears in the NE-originated RREs. For both types of events, the strongest $I_c$ appears outside the BJP. RREs from the SW correspond to stronger large-scale circulations and water vapor transport than those from the NE.

The studied heavy rainfall events with different origins present quite different features in both the rainfall itself and its corresponding circulations. During the study period (2009–2016), the SW-originated events usually occur during the traditional flood season in North China, which is from late July to mid August; long-duration
rainfall events constitute a much larger portion of the total rainfall than the NE-originated events, and the early-morning diurnal peaks are more obvious in the SW-originated events. According to Yuan et al. (2014), the rainfall that occurs during the flood season is characterized by nocturnal rainfall peaks and a long duration, which is consistent with the RREs from the SW. Additionally, in the traditional flood season, the subtropical high and westerly winds extend to their northern most positions during the summer, and the southwesterly winds of the northwestern part of the subtropical high enhance the moisture transport from southern China to North China (Ding and Chan, 2005). This type of circulation is also found in the major Baiyu (in Japan) and Changma (in Korea) rainy seasons (Oh et al., 1997; Ninomiya and Shibagaki, 2007). Coincidently, this characteristic circulation in the traditional flood season also appears in the SW-originated RREs. The stronger large-scale forcing in the SW-originated events favors a wider coverage of rainfall and higher $I_c$ values in SW-originated events, as well as a large proportion of intense rainfall to the total rainfall amount. The rainfall systems originated from the NE cover a relatively smaller horizontal span, but the maximum $I_c$ is stronger. This type of strong rainfall event tends to occur before the start of the flood season in June and July, and the afternoon rainfall peak is more apparent. The relatively smaller low-level wind speeds associated with the NE-originated RREs may be greatly affected by the cancellation of winds from different directions in May–September, because no strong high-level steering systems were found. The rainfall events from the NE may be greatly influenced by strong convective instability. The maximum CAPE in the BJP averaged among all the NE-originated events is about 1109.68 J kg$^{-1}$, while the mean maximum CAPE of the SW-originated events is 755.03 J kg$^{-1}$. With this knowledge, namely, a better understanding of the links between rainfall propagation and leading circulation structures, is obtained and could provide valuable help in future analysis and forecasting of rainfall over the BJP.

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REFERENCES

Bao, X. H., F. Q. Zhang, and J. H. Sun, 2011: Diurnal variations of warm-season precipitation east of the Tibetan Plateau over China. Mon. Wea. Rev., 139, 2790–2810, doi: 10.1175/mwr-d-11-00061.1.

Carbone, R. E., J. D. Tuttle, D. A. Ahijevych, et al., 2002: Inferences of predictability associated with warm season precipitation episodes. J. Atmos. Sci., 59, 2033–2056, doi: 10.1175/1520-0469(2002)059<2033:ipawwp>2.0.co;2.

Chen, H. M., R. C. Yu, J. Li, et al., 2010: Why nocturnal long-duration rainfall presents an eastward-delayed diurnal phase of rainfall down the Yangtze River valley. J. Climate, 23, 905–917, doi: 10.1175/2009jcli3187.1.

Chen, M. X., Y. C. Wang, F. Gao, et al., 2012: Diurnal variations in convective storm activity over contiguous North China during the warm season based on radar mosaic climatology. J. Geophys. Res. Atmos., 117, D20115, doi: 10.1029/2012jd018158.

Chen, S., Y. C. Wang, W. L. Zhang, et al., 2011: Intensifying mechanism of the convective storm moving from the mountain to the plain over Beijing. Meteor. Mon., 37, 802–813. (in Chinese)

Ding, Y. H., and J. C. L. Chan, 2005: The East Asian summer monsoon: An overview. Meteor. Atmos. Phys., 89, 117–142, doi: 10.1007/s00703-005-0125-z.

Du, Y., and G. X. Chen, 2019: Heavy rainfall associated with double low-level jets over southern China. Part II: Convection initiation. Mon. Wea. Rev., 147, 543–565, doi: 10.1175/ mwr-d-18-0102.1.

Findlater, J., 1969: A major low-level air current near the Indian Ocean during the northern summer. Quart. J. Roy. Meteor. Soc., 95, 362–380, doi: 10.1002/qj.49709540409.

Gao, C. C., Y. Y. Li, and H. W. Chen, 2019: Diurnal variations of different cloud types and the relationship between the diurnal variations of clouds and precipitation in central and East China. Atmosphere, 10, 304, doi: 10.3390/atmos10060304.

He, H. Z., and F. Q. Zhang, 2010: Diurnal variations of warm-season precipitation over northern China. Mon. Wea. Rev., 138, 1017–1025, doi: 10.1175/2010mwr3356.1.

He, J., F. Q. Zhang, X. C. Chen, et al., 2019: Development and evaluation of an ensemble-based data assimilation system for regional reanalysis over the Tibetan Plateau and surrounding regions. J. Adv. Model. Earth Syst., 11, 2503–2522, doi: 10.1029/2019ms001665.

Hersbach, H., and D. Dee, 2016: ERA5 reanalysis is in production. ECMWF Newsletter, 147, 7–7.

Hersbach, H., B. Bell, P. Berrisford, et al., 2019: Global reanalysis: goodbye ERA-Interim, hello ERA5. ECMWF Newsletter, 159, 17–24.

Higgins, R. W., Y. Yao, E. S. Yarosh, et al., 1997: Influence of the Great Plains low-level jet on summertime precipitation and moisture transport over the central United States. J. Climate, 10, 481–507, doi: 10.1175/1520-0442(1997)010<0481:itgplj>2.0.co;2.

Kuo, H. L., and K. L. Seitter, 1985: Instability of shearing geostrophic currents in neutral and partly unstable atmospheres. J. Atmos. Sci., 42, 331–345, doi: 10.1175/1520-0469(1985)042<0331:iosgc>2.0.co;2.

Li, J., and R. C. Yu, 2014: A method to linearly evaluate rainfall frequency–intensity distribution. J. Appl. Meteor. Climatol., 53, 928–934, doi: 10.1175/jamc-d-13-0272.1.

Li, J., R. C. Yu, and J. J. Wang, 2008: Diurnal variations of summer precipitation in Beijing. Chinese Sci. Bull., 53, 1933–1936, doi: 10.1007/s11434-008-0195-7.

Limaitre, Y., and P. Brovelli, 1999: Role of a low level jet in triggering and organizing moist convection in a baroclinic atmo-
sphere. A case study: 18 May 1984. J. Atmos. Sci., 47, 82–100, doi: 10.1175/1520-0469(1990)047<087:icafct>2.0.co;2.
Liu, Y., J. Xia, C. X. Shi, et al., 2009: An improved cloud classification algorithm for China’s FY-2C multi-channel images using artificial neural network. Sensors, 9, 5558–5579, doi: 10.3390/s90705558.
Luo, Y. L., M. W. Wu, F. M. Ren, et al., 2016: Synoptic situations of extreme hourly precipitation over China. J. Climate, 29, 8703–8719, doi: 10.1175/jcli-d-16-0057.1.
Ninomiya, K., and Y. Shibagaki, 2007: Multi-scale features of the Meiyu-Baiu front and associated precipitation systems. J. Meteor. Soc. Japan, 85B, 103–122, doi: 10.2151/jmsj.85b.103.
Nitta, T., and S. Sekine, 1994: Diurnal variation of convective activity over the tropical western Pacific. J. Meteor. Soc. Japan, 72, 627–641, doi: 10.2151/jmsj1965.72.5_627.
Oh, T. H., W. T. Kwon, and S. B. Ryoo, 1997: Review of the researches on changma and future observational study (kormex). Adv. Atmos. Sci., 14, 207–222, doi: 10.1007/s00376-997-0020-2.
Nitta, T., and S. Sekine, 1994: Diurnal variation of convective activity over the tropical western Pacific. J. Meteor. Soc. Japan, 72, 627–641, doi: 10.2151/jmsj1965.72.5_627.
Oh, T. H., W. T. Kwon, and S. B. Ryoo, 1997: Review of the researches on changma and future observational study (kormex). Adv. Atmos. Sci., 14, 207–222, doi: 10.1007/s00376-997-0020-2.
Rossow, W. B., and R. A. Schiffer, 1999: Advances in understanding clouds from ISCCP. Bull. Amer. Meteor. Soc., 80, 2261–2288, doi: 10.1175/1520-0477(1999)080<2261:aaicuc>2.0.co;2.
Saulo, C., J. Ruiz, and Y. G. Skabar, 2007: Synergism between the low-level jet and organized convection at its exit region. Mon. Wea. Rev., 135, 1310–1326, doi: 10.1175/mwr3317.1.
Shen, Y., P. Zhao, Y. Pan, et al., 2014: A high spatiotemporal gauge–satellite merged precipitation analysis over China. J. Geophys. Res. Atmos., 119, 3063–3075, doi: 10.1002/2013jd020686.
Yin, S. Q., D. L. Chen, and Y. Xie, 2009: Diurnal variations of precipitation during the warm season over China. Int. J. Climatol., 29, 1154–1170, doi: 10.1002/joc.1758.
Yin, S. Q., W. J. Li, D. L. Chen, et al., 2011: Diurnal variations of summer precipitation in the Beijing area and the possible effect of topography and urbanization. Adv. Atmos. Sci., 28, 725–734, doi: 10.1007/s00376-010-9240-y.
Yu, R. C., J. Li, H. M. Chen, et al., 2014: Progress in studies of the precipitation diurnal variation over contiguous China. J. Meteor. Res., 28, 877–902, doi: 10.1007/s13351-014-3272-7.
Yu, R. C., H. M. Chen, and W. Sun, 2015: The definition and characteristics of regional rainfall events demonstrated by warm season precipitation over the Beijing Plain. J. Hydrometeor., 16, 396–406, doi: 10.1175/jhm-d-14-0086.1.
Yuan, W. H., R. C. Yu, H. M. Chen, et al., 2010: Subseasonal characteristics of diurnal variation in summer monsoon rainfall over central eastern China. J. Climate, 23, 6684–6695, doi: 10.1175/2010jcli3805.1.
Zhong, L. Z., R. Mu, D. L. Zhang, et al., 2015: An observational analysis of warm-sector rainfall characteristics associated with the 21 July 2012 Beijing extreme rainfall event. J. Geophys. Res. Atmos., 120, 3274–3291, doi: 10.1002/2014jd022686.