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Spatial and diurnal characteristics of summer rainfall over Beijing Municipality based on a high-density AWS dataset

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ABSTRACT: On basis of quality-control of hourly rainfall dataset of Automatic Weather Stations (AWSs) for the last 4 years (2007–2010), the spatial and diurnal characteristics of summer rainfall in Beijing Municipality (BJM) is analyzed. Results show that the short-duration heavy rainfall events dominate summer rainfall in the study area. Rainfall events with 1–3 h duration make a large contribution to both frequency and amount of summer rainfall, and the total rainfall amount in summer fall almost in the events with duration less than 6 h. Two peaks in diurnal variation of rainfall event frequency are evident, with one in early morning and another in later evening, but only one peak in later evening occurs for diurnal variation of rainfall amount. The exact timing and magnitudes of the peaks vary from one station to another probably due to the influence of the complicated terrains and geographical conditions. Except for the southeast area of the BJM, however, the highest frequency of rainfall events always occurs in evening between 1900 and 2300 (Local Standard Time, or LST), almost consistent to the occurrence time of the maximum rainfall amount. The peak of rainfall event frequency over the southeast area is generally in early morning (0300–0500 LST) which might have been related to the combined influences from land-sea breeze and urbanization. Copyright © 2012 Royal Meteorological Society

KEY WORDS rainfall events; spatial distribution; diurnal cycle; summer; Beijing Municipality

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1. Introduction

The observed increase in frequency and intensity of extreme precipitation events over some regions of northern Hemisphere has aroused great concerns about the possible effects of anthropogenic climate change (Trenberth *et al*., 2007; Li *et al*., 2008). Extreme precipitation can lead to wide spread damages in the form of floods and the associated destructions, particularly in vulnerable regions of the world. What is important for the damages to occur, however, is not only the frequency and intensity of the extreme precipitation events, but also the timing and magnitude of rainfall events in diurnal variation during rainy season of a region.

In previous studies of long-term variation, the frequency and intensity of intense precipitation events are generally defined by daily precipitation totals based on the daily rainfall records (Trenberth *et al*., 2007). The procedure is not enough to reveal the characteristics of the precipitation events. If daily total precipitation of 25 mm is evenly spread in the 24 h of a day, e.g. it has less possibility to produce damage than that concentrated in a shorter time period. On the other hand, the time when precipitation occurs intensively during particular hours of a day is usually characterized by certain local dynamical and thermal atmospheric conditions. Kanae *et al*. (2004) showed that the extreme intense precipitation events concentrated in a shorter time period of a day can more effectively represent the observed trends. Fujibe (1998), Dai *et al*. (1999) and Sato and Takahashi (2000) pointed out that a detailed analysis on diurnal variation of precipitation events is helpful to the understanding of local climatic dynamics and the parameterizations of climate models.

Faiers *et al*. (1994) examined 3 and 24 h precipitation totals over Louisiana and reported significant difference in storm frequency according to weather types, but with no significant difference in precipitation intensity. Winkler *et al*. (1988) noted the relative strengthening of amplitude with increase in intensity of hourly precipitation events over the central and eastern United States. Hu (2003) showed a multi-decadal variation in the diurnal rainfall pattern in the central United States, with the decades characterized by the southerly flow witnessing a rainfall peak in the midnight hour, and the decades with weakened southerly flow having a broad plateau of rainfall in the late night/early morning hours. On the basis of hourly rain record, the geographically varied characteristics of diurnal variation of the warm-season precipitation events over mainland China were analyzed and

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summarized by Yu *et al*. (2007). Zhou *et al*. (2008) found that the diurnal phases of precipitation frequency and intensity in China are similar to those of rainfall amount in most regions, except for the middle Yangtze River valley. Yuan *et al*. (2010) showed that the rainfall in the monsoon rain belt of central eastern China is dominated by the long-duration rainfall events (>7 h) with early-morning peaks.

Li *et al*. (2008) made a detailed analysis of the climatic characteristics and secular trends of diurnal variations of summer precipitation in Beijing area. They showed the relatively high values of rainfall amount and rainfall frequency from late afternoon to early morning, and two separate peaks in the late afternoon and early morning. They also found that the rainfall during late afternoon to midnight mainly comes from the short-duration rainfall events (1–6 h), while the rainfall during midnight to early morning occurs mostly in the long-duration rainfall events (>6 h). Although the total rainfall amount from long-duration events decreased over the past 40 years, which from short-duration events increased significantly (Li *et al*., 2008). Yin *et al*. (2011) showed that sites on the plain of Beijing area display night rain peaks in summer, whereas those in the mountainous area witness afternoon peaks of precipitation. They further suggested that the diurnal precipitation peaks are probably modulated by mountain-valley and urban-country circulations. Wu *et al*. (2000) investigated the basic features of the short duration precipitation in BJM and found that the short-duration rainfall events are the dominant rainfall mode during summer over the area analyzed.

However, Li *et al*. (2008), Yin *et al*. (2011) and Wu *et al*. (2000) only used summer hourly rainfall data from less than 20 stations in their analyses of Beijing area, and this made it difficult to learn the detailed spatial structure of the diurnal variation of summer rainfall. In fact, spatially sufficient observations of hourly precipitation with enough length of records are extremely important for analyzing the characteristics of regional and local precipitation. In this paper, we apply a dataset of densely distributed Automatic Weather Stations (AWSs) for the time period 2007–2010 to investigate the spatial and diurnal variability of summer rainfall in BJM, and we are able to reveal a few of new phenomena which have not been found in the previous analyses.

2. Data and analysis method

Hourly precipitation data from 2007 to 2010 are collected from 185 stations across BJM. Metadata are obtained from the Meteorological Information Center (MIC), Beijing Meteorological Bureau. Up to now, there has not been a good method to make quality control for hourly precipitation record due to the extreme locality of precipitation. A reasonable procedure is to correct the error records with multi-source data, including radar data and satellite data. That will demand a time-consuming work, which is well beyond the analysis of this paper.

The AWS dataset have been preliminarily quality-controlled by the MIC, mainly through applying regionally climatological extreme values for checking the possibly wrong records. Because of the abundant stations available, the incredible stations were taken out of the dataset directly. We further discriminate the data by using the methods of threshold values and manual identification. On the basis of the observational records and the climatological features of precipitation in BJM, the hourly records exceeding 50 mm were considered as suspicious, and they were checked, and adjusted if proved wrong by comparing the records of the adjacent stations. After the adjustments, the peak values of each of the summer months from 2007 to 2010 is set to be 68.2 mm for June, 82.6 mm for July, and 95.9 mm for August.

In order to minimize the impact of missing records on the analysis, only those with missing values less than 3% of the total records for the 4 years are chosen for use. All of the missing records for the stations chosen have been reconstructed by using the interpolation method of inverse distance weighting. Although the reconstruction is necessary for guaranteeing the completeness of the dataset and for raising the statistical confidence, we find through a comparison of the reconstructed and unreconstructed data that there is little difference between the analysis results.

After the controlling of the data quality, an hourly precipitation dataset of totally 123 stations with information of accurate locations and heights is obtained and used for this study. Figure 1 shows the distribution of the 123 stations. Denser observations are located in the central urban area and the nearby areas represented by Haidian (HD), Fengtai (FT) and Chaoyang (CY), and the stations in the western and northern mountainous areas are relatively sparse.

Most rainfall events occur in warm season, especially in summer, in BJM. The analysis is therefore focused to summer, but the data of spring and autumn are also used for comparison with the rainy season. The characteristics of the summer rainfall, especially its diurnal variation feature, are examined. The meteorological seasons of spring (March–May), summer (June–August) and autumn (September–November) are used. The time used here refers to the Local Standard Time (LST), which is equal to the China Standard Time.

The hourly rainfall event in this study is defined as rain record with more than 0.1 mm precipitation amount accumulated during the past an hour, and it is further assumed that the rainfall event has continuous durations without any intermittence. The accumulated rainfall duration is defined as the total hours with precipitation within any time periods concerned, and rainfall event duration is defined as the number of continuous hours between the beginning time and end time of any precipitation event. In order to simplify the analysis, the rainfall event duration is further divided into four different categories, which are respectively, 1–3 h, 4–6 h, 7–12 h, and more than 12 h. The rainfall with

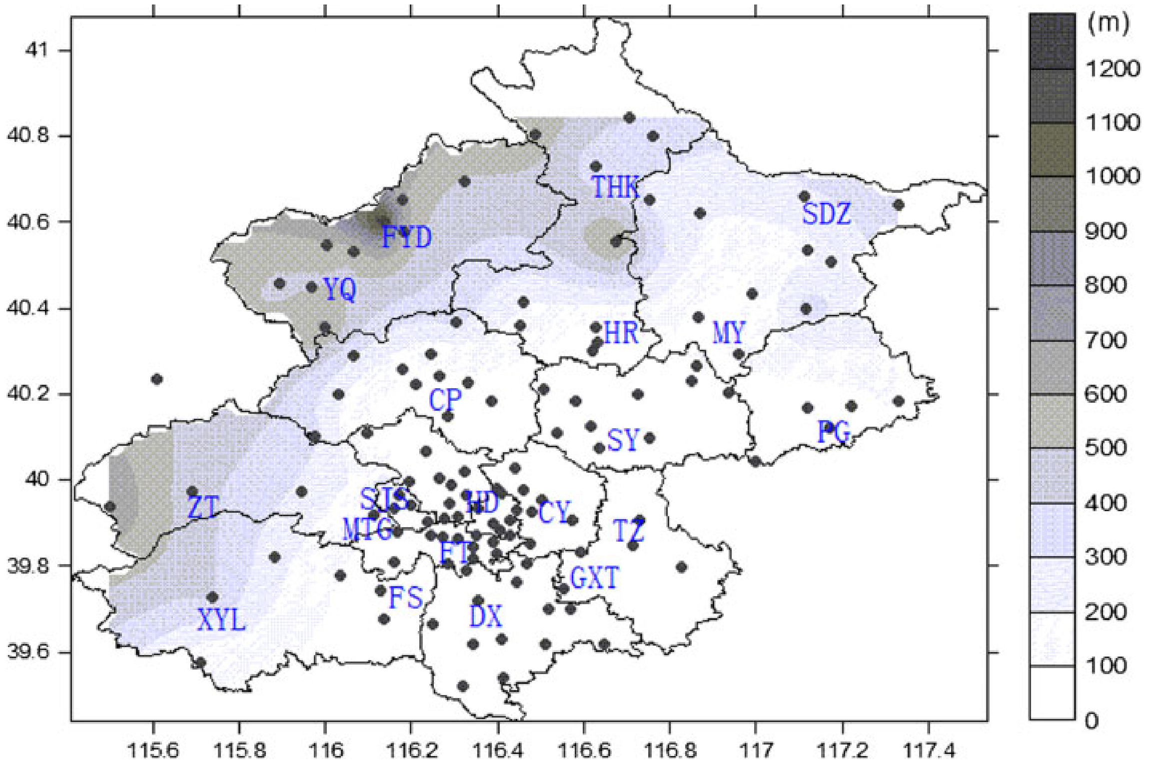

Figure 1. Distribution of the 123 stations with hourly precipitation data over Beijing. The isolines are contours indicating the terrain height. Also shown are the 20 meteorological stations with at least 30 year records of rainfall, with the abbreviations of their names marked. GXT – Guanxiangtai, HD – Haidian, FT – Fengtai, DX – Daxing, SJ – Shijingshan, CP – Changping, MTG – Mentougou, CY – Chaoyang, FS – Fangshan, TZ – Tongzhou, SY – Shunyi, YQ – Yanqing, HR – Huairou, THK – Tanghekou, XYL – Xiayunling, ZT – Zhaitang, MY – Miyun, PG – Pinggu, SDZ – Shangdianzi, FYD – Foyeding. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

event duration of 0–60 min is regarded as a 1 h event. Similarly, in order to analyze the contribution of different hourly rainfall amount to daily precipitation, the hourly precipitation events are classified referring to previous studies (Wu *et al*., 2000; Fu *et al*., 2008; Gong *et al*., 2011), the local rainfall characteristics and the definition of 24-h grading precipitation. They are thus divided into six grades of rainfall amount which are respectively slight (≤1 mm), small (1.1–5.0 mm), moderate (5.1–10 mm), large (10.1–25 mm), heavy (25.1–50 mm) and torrential (more than 50 mm) rainfall event.

It is worth noting that there are radically different kinds of the precipitation grading methods. Fu *et al*. (2008) proposed a method of grading precipitation when they analyzed the features of hourly rainfall, and the grading standards is already experimentally applied to the CMA meteorological operations. Our method proposed in this paper partially refers to that by Fu *et al*. (2008). However, precipitation intensity depends on the rainfall amount and the time periods concerned, and it also varies from one place to another due to the different climatic conditions. There has been no unified criterion for the short duration precipitation grading. Gong *et al*. (2011) regarded the hourly rainfall amount more than 10 mm as the extreme precipitation event. Wu *et al*. (2000) proposed that accumulated precipitation more than 15 mm in 1 h can be considered as heavy rain. The method used in our analysis takes the characteristics of hourly rainfall and the rainfall impacts on economics and society in the study region into a sufficient consideration, but it could be evidenced and improved in the future studies.

Finally, in the analysis on the frequency and amount of the diurnal variation of summer rainfall, the time when maximum and minimum precipitation occurs is just simply represented by the time digit value for convenience.

3. Spatial characteristics of summer rainfall over BJM

The mean accumulated rainfall duration, amount and hourly rainfall intensity for summer over BJM are shown in Figure 2. It is evident that the distributions of the summer mean accumulated rainfall duration and rainfall amount are rather different. To some extent, they are in out of phase to each other. The accumulated rainfall duration is generally larger in the northwestern and northern mountainous areas, with the stations near Huairou (HR) and Miyun (MY) registering the largest mean accumulated rainfall duration of more than 200 h in summer. A secondary centre of large mean accumulated rainfall duration is the western mountainous area near CP and YQ. In the plain areas of the southeast, the mean accumulated rainfall duration is usually less than 150 h.

The large summer mean rainfall amount centres in the mountainous areas of the northeast, with the largest records, around 350 mm, occurring in stations near PG

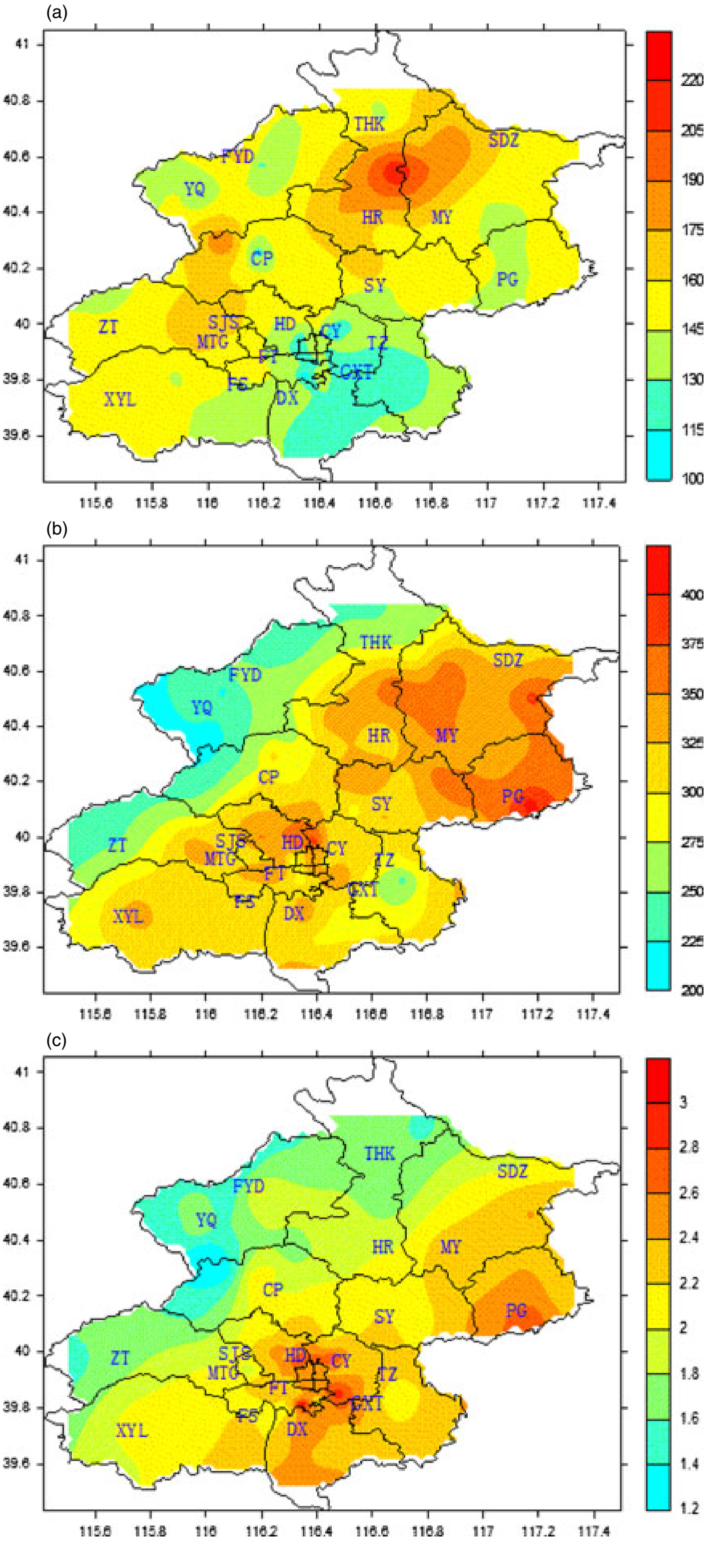

Figure 2. Spatial distributions of the summer mean accumulated rainfall duration (unit: h) (a), rainfall amount (Unit: mm) (b) and rainfall intensity (unit: mm/h) (c) in Beijing Municipality during 2007–2010. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

and MY. An obvious large-value centre of mean rainfall amount appears in the northeastern part of the built-up area of BJM, with the largest record surpassing 350 mm. The northwestern mountainous areas witness the lowest mean precipitation amount, generally less than 250 mm. A small area with low mean rainfall is observed in the southwestern area. The most obvious feature in hourly rainfall intensity is the distribution of high-value records in the built-up area of BJM and the nearby sites. The mean maximum intensity in the areas reaches more than 24 mm h^{-1}. A secondary centre is seen in eastern most part of the study region. Similar to the mean rainfall amount, remarkably low-value stations mostly distribute in northwestern mountainous areas.

The spatial pattern of the summer mean accumulated rainfall duration, rainfall amount and hourly rainfall intensity in BJM is mainly controlled by the terrains and land use change. The warm southeasterly and southwesterly can be elevated by the mountains of the west and the north, resulting in the formation of summer rainfall in the windward slopes and the buffering of rainfall in the leeward slopes (Xu *et al*., 2006). The relatively large rainfall amount in the northeastern part of built-up area of BJM might have partly resulted from the urbanization effects which can enhance the convective instability of the lower troposphere.

Table I. Percentage contributions of rainfall events with different duration to accumulated rainfall duration and total rainfall amounts for summer, spring and autumn.

Duration	1–3 h	4–6 h	6–12 h	12 h-
Summer				
Accumulated rainfall duration	45.2	21.5	21.8	11.5
Total rainfall	33.5	25.6	26.9	14.1
Spring				
Accumulated rainfall duration	38.4	21.1	19.2	21.4
Total rainfall	25.9	25.0	19.0	30.1
Autumn				
Accumulated rainfall duration	29.2	19.0	31.9	19.9
Total rainfall	17.5	19.2	41.1	22.2

4. The characteristics of rainfall event duration

Analysis on the spatial distribution of rainfall event duration is helpful to the understanding of mechanism of precipitation variation (Yu *et al*., 2007). The percentage contributions to accumulated rainfall duration and total rainfall with different durations for summer, spring and autumn are shown in Table I.

The contribution of the rainfall events with 1–3 h duration in summer takes the highest percentage among three seasons both in frequency and amount. More than half of the rainfall events have a duration time of 1–6 h, while the long-duration (12 h–) rainfall events only account for less than 15%. There exist obvious differences in the four different-duration rainfall event compared to the other seasons of the warm season. The contributions of the short-duration rainfall events are obviously larger in summer than in spring and autumn. For spring, the short-duration rainfall (1–3 h) captures the highest percentage of the accumulated rainfall duration (38.4%), but the highest percentage of the total rainfall comes from the long-duration rainfall (12 h–), reaching 30.1%. For autumn, the medium- and long-duration rainfall events (6 h–) play the most important roles both in the accumulated rainfall duration and in total rainfall amount.

It is therefore clear that the short-duration rainfall events are the most basic summer rainfall mode over BJM in terms of the accumulated rainfall duration (or frequency), which is in agreement with the previous studies (Yu *et al*., 2007; Li *et al*., 2008). In view of rainfall amount and its contribution to the total rainfall, however, the medium- and long-duration rainfall events (6 h–) are more important in spring and autumn, in spite of the fact that it still plays a major role for the short-duration rainfall event for summer. More attention therefore should be paid to the summer short-duration rainfall in the flooding management of BJM.

Figure 3 shows the contributions of four different-duration rainfall events to the accumulated rainfall duration in summer over BJM. It is clear that 1–3 h rainfall events dominate the summer rainfall in the study region. About 35–55% of the accumulated summer rainfall duration comes from the short-duration rainfall events, while the contribution from the rainfall events with longest-duration is less than 21%. The 1–3 h duration rainfall events mainly prevail in northwestern and southwestern areas, while northeastern part of BJM witnesses the fewest hours of the short-duration rainfall events. Wu *et al*. (2000) also found that the short-duration rainfall events are the most basic summer rainfall mode in urban area of Beijing. The 4–6 h duration rainfall events mostly occur in the northeastern and southeastern parts of the study region, and they occur less frequently in the west, including the areas near CP and FS, a clear opposite pattern to the 1–3 h rainfall events. A more concentrated distribution of rainfall duration in the northeast is seen for the 7–12 h rainfall events, but the rainfall events with more than 12 h duration appears to be similar to those of 1–3 h duration rainfall events. Therefore, it is clear that very short and very long duration rainfall events generally more frequently occur in the western BJM, and this can be related to the influence of the mountains. The terrains might be a crucial influential factor of the spatial distribution of hourly rainfall duration in BJM.

Figure 4 shows the spatial distributions of the contributions of four different-duration rainfall amounts to the total rainfall amounts in summer over BJM. The 1–3 h duration rainfall amounts generally make higher contribution to the total rainfall in urban areas and northwestern areas. The 4–6 h duration rainfall contributes more in northeastern areas including those near PG and MY. Approximately similar pattern can be seen for the contribution from 7 to 12 h duration rainfall amount, but with a centre more close to the urban areas. For the rainfall events with duration of more than 12 h, the larger contributions appear in the western and southwestern areas.

Therefore, the short duration rainfall events are the major contributor to the total rainfall events both in durations and amount in summer over BJM. The rainfall events with duration less than 6 h generally account for more than 50% contribution to the accumulated rainfall duration and total rainfall amount in BJM. It is also interesting to note that the spatial pattern of the percentage contribution of 1–3 h duration rainfall amount is characterized by the obviously high values over the urban areas. The feature might have been attributed to the relatively higher temperature associated with Urban

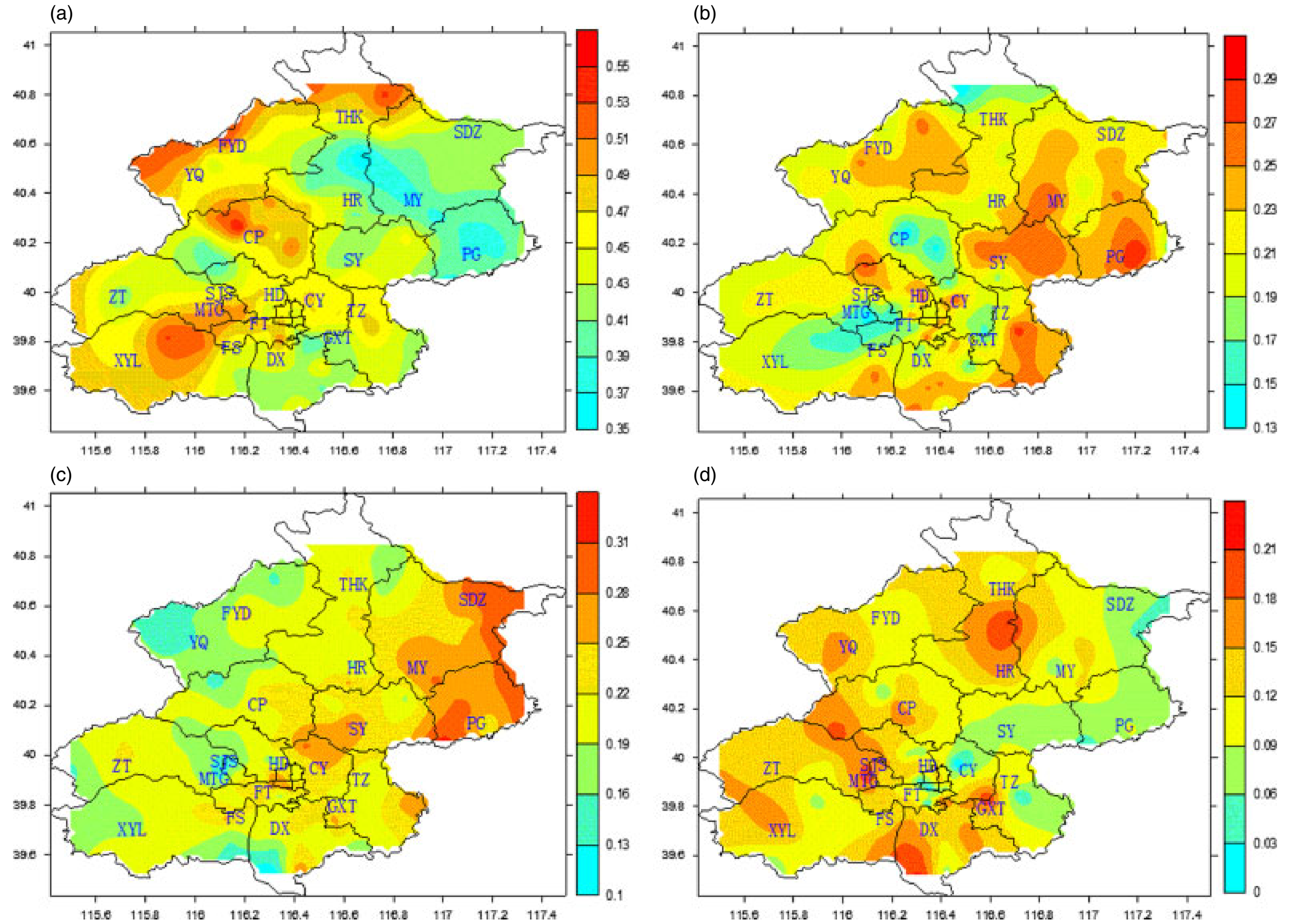

Figure 3. The contributions of four different-duration rainfall events to the accumulated rainfall duration in summer over Beijing Municipality. (a) 1–3 h; (b) 4–6 h; (c) 7–12 h and (d) 12 h–. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Heat Island (UHI) effect in urban areas as indicated in previous studies (Ren *et al*., 2007; Liu *et al*., 2009a, 2009b).

5. Contributions of different categories of rainfall events

The intensity of a rainfall event is decided by the time it lasts and the amount accumulated in the time. For a certain it is important to know the relative contribution of rainfall events with different lasting time (h) to the total frequencies and amounts. Figures 5 and 6 show the contributions of rainfall event frequencies and amounts of the six categories to the total rainfall frequencies and amounts in summer over BJM.

The distribution of percentage contribution of the rainfall events to the total rainfall frequencies reveals that the change in percentage contributions with the lasting time largely depends on the categories of rainfall amounts (Figure 5). It is obvious from Figure 5 that the slight and small rainfall events (≤5 mm an hour) takes a rather large contribution to the total rainfall events in terms of frequency, and the heavy and torrential rainfall events (more than 25 mm an hour) contribute much less in combination.

For slight rainfall, the percentage contributions obviously decease with the lasting time of the category of rainfall. Small rainfall sees a very large fluctuation, but a general decrease for the events with lasting time less than 9 h, and an increase and large variability for the events with lasting time more than 9 h. It seems that the small rainfall event represents a transition category between slight rainfall and moderate rainfall, and the occurrence probability of the small rainfall events does not closely depend on the lasting time.

The more intense hourly rainfall events are characterized by the marked rising of frequencies with the lasting time, with moderate and large rainfall events undergoing an even more rapid increase between 1 and 6 h. The change of frequencies displays a monograph rising trend for torrential rainfall events, and no platform appearing in cases of the moderate, large and heavy rainfall events can be found any more. These indicate that the more intense the rainfall events, the longer time will they usually take. There are seldom heavy and torrential rainfall events which actually occur within less than 3 h. When a rainfall process of more than 10 mm in 3 h occurs, the possibility is high that it will become an extreme rain event. Less than 3 or 6 h seem a suitable time length for analyzing the short-duration rainfall events over BJM.

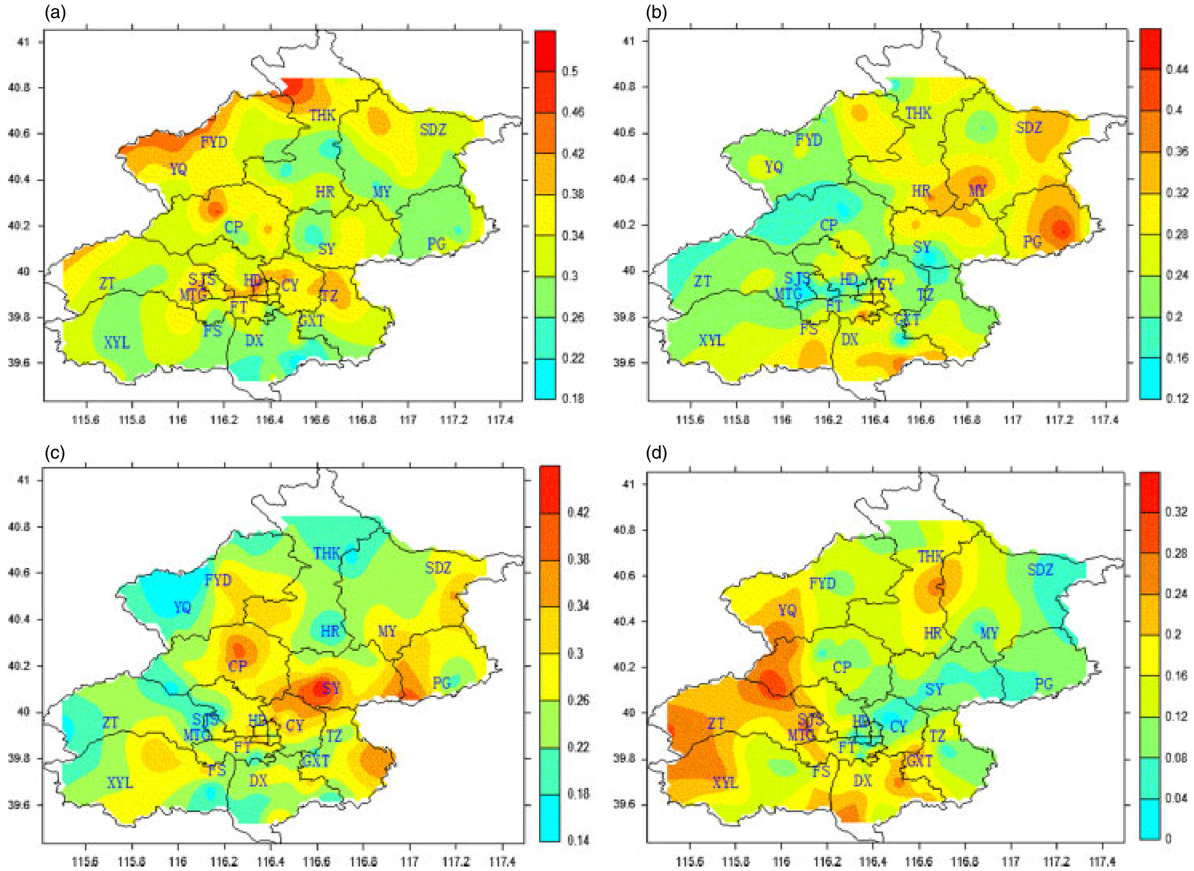

Figure 4. Contributions of four different-duration rainfall amounts to the total rainfall amounts in summer over Beijing Municipality. (a) 1–3 h; (b) 4–6 h; (c) 7–12 h and (d) 12 h–. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

This is approximately accord with the previous study by Shouraseni (2009) who defined 30 mm rainfall during 12 h as heavy rainfall event.

Compared to the relative contributions of the rainfall events to the total rainfall frequencies, the percentage contribution of rainfall amounts to the total rainfall amount in summer has a few of distinguished features of their own (Figure 6). The average relative contribution of slight rainfall to the total rainfall amount is very small, and the major contributions come from the other categories of rainfall, particularly from large and heavy rainfall.

For the rainfall events with less than 10 mm an hour, the relative contributions decline rapidly with the lasting time within the first 3–9 h, indicating that the short-duration rainfall makes an important contribution to total rainfall amount. However, the percentage contributions increase rapidly at first and then come into a platform at 9 h and 16 h for heavy rainfall events (25.1–50 mm an hour) and torrential rainfall events (more than 50 mm an hour) respectively. In the platform periods, the contribution to total rainfall amount undergoes little change with increase of the lasting time. This implies that 25 mm amount might be a key value for the short duration rainfall events in view of the total rainfall amount. Usually the cases within 12 h are taken as short time rainfall. A particular feature takes place in large rainfall events (10.1–25 mm an hour). Percentage contribution to total rainfall amount has an obvious peak during 3–6 h, which cannot be found for the other categories, implying that the large rainfall event represents a transition category between moderate and heavy rainfall events, and the relative contribution of the large rainfall events with the lasting time of 3–6 h to the total rainfall are extremely high.

6. Diurnal rainfall cycle

The diurnal variations of summer mean rainfall frequency and rainfall amount of over BJM are shown in Figure 7. The main characteristics of the diurnal variation curves in Figure 7 are somewhat similar. They rise up to highest level around 2100 LST in evening and fall down to lowest level around 0800 LST in morning. The lower values generally appears in the time from 0500 to 1300 LST. This feature is more notable in the mean rainfall, with 37.5% of time length of a day only contributing 27.9% of daily mean rainfall. A midnight to early morning maximum in frequency of precipitation occurrence in Beijing was also reported in other researches.(Yin *et al*., 2011), but our analysis shows a clearer diurnal cycle in daily total rainfall amount in terms of timing and magnitude of the variation.

However, differences between the two diurnal rainfall variation curves are also evident. The curve of rainfall

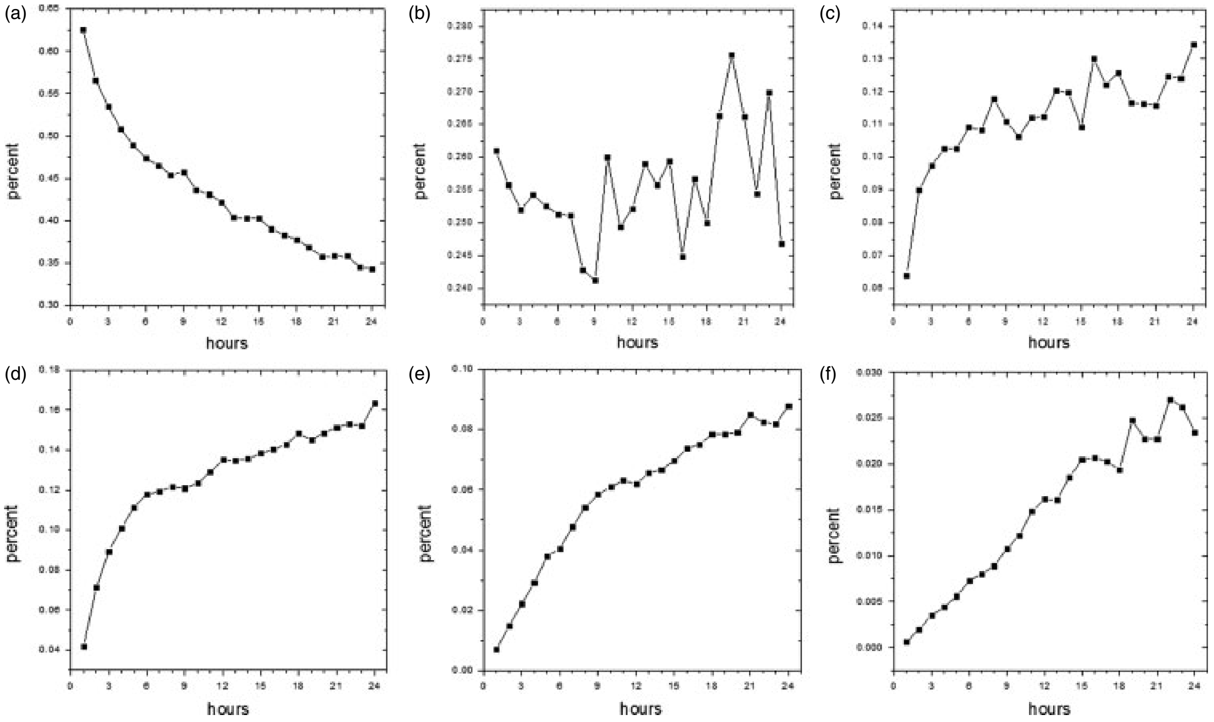

Figure 5. Percentage contributions of rainfall events of the 6 categories to the total rainfall frequencies in summer over Beijing Municipality. (a) Slight ($\leq$1 mm), (b) small (1.1–5.0 mm), (c) moderate (5.1–10 mm), (d) large (10.1–25 mm), (e) heavy (25.1–50 mm) and (f) torrential (more than 50 mm).

frequency has two peaks appearing respectively in early morning and later evening, but merely one peak develops in later evening for the diurnal variation of rainfall. The maximum and minimum of diurnal rainfall frequency are around 2000 and 0800 LST, respectively. Contrast to the diurnal variation of rainfall frequency, the maximum of diurnal rainfall amount appears almost 2 h later (at about 2200 LST), and the minimum appears 3 h earlier (at about 0500 LST). It is also notable that the diurnal rainfall amount series has a smaller inter-hourly variability, indicating a relatively high signal-to-noise radio and predictability.

The nocturnal peaks in mean rainfall frequency and rainfall amount are likely to be caused by an interaction among the diurnal variation of local thermal instability and convection in summer, mountain-valley breeze circulation and the UHI circulation. The mountain-valley breeze and UHI circulations were suggested as important factors for the diurnal variation of summer rainfall over BJM (Li *et al*., 2008). The UHI effect and UHI circulation are usually strong at night and weak after sunrise (Oke, 1982; Kalnay and Cai, 2003), with the strongest UHI circulation generally occurring in the early morning. The UHI effect and UHI circulation might have been tuning the diurnal tone of the summer rainfall in BJM.

On the basis of the classification of hourly rainfall amounts mentioned above, the percentage contributions of the six categories of rainfall events to the 24 h rainfall frequency and rainfall amount are analyzed for four periods of hours in a day. The four periods include early morning (0300–0800 LST), late morning to early afternoon (0900–1400 LST), late afternoon to evening (1500–2000 LST) and night (2100–0200 LST). The region-averaged percentage contributions of the different rainfall events to the total rainfall frequency and amount for the four periods of a day are shown in Figure 8.

It is obvious that all categories of the rainfall events are more likely to occur during periods of late afternoon to evening (1500–2000 LST) and night (2100–0200 LST) over BJM. The relative contributions of the rainfall events to the total rainfall frequency and amount during early morning (0300–0800 LST) and late morning to early afternoon (0900–1400 LST) are smaller, and the possibility is low for heavy and torrential rainfall events to occur during late morning to early afternoon. During the period with high possibility of occurrence of rainfall events, the more intense the hourly rainfall events, the more likely they take place at night time (2100–0200 LST). It is therefore evident that the percentage contributions of the rainfall events to the total rainfall frequency and amount generally decrease with the increase in hourly rainfall intensity during 0300–1400 LST, but they usually increase with the increase in hourly rainfall intensity during 1500–0200 LST.

The distributions of maximum and minimum time (LST) of summer diurnal rainfall variation over BJM are shown in Figure 9. The maximum time for summer rainfall event frequency propagates from northwest to southeast, with the northwest occurring in early evening, the central and southwest in later evening and the southeast in late night hours. Except for the southeast (including TZ and DX) where a nearly uniform maximum time

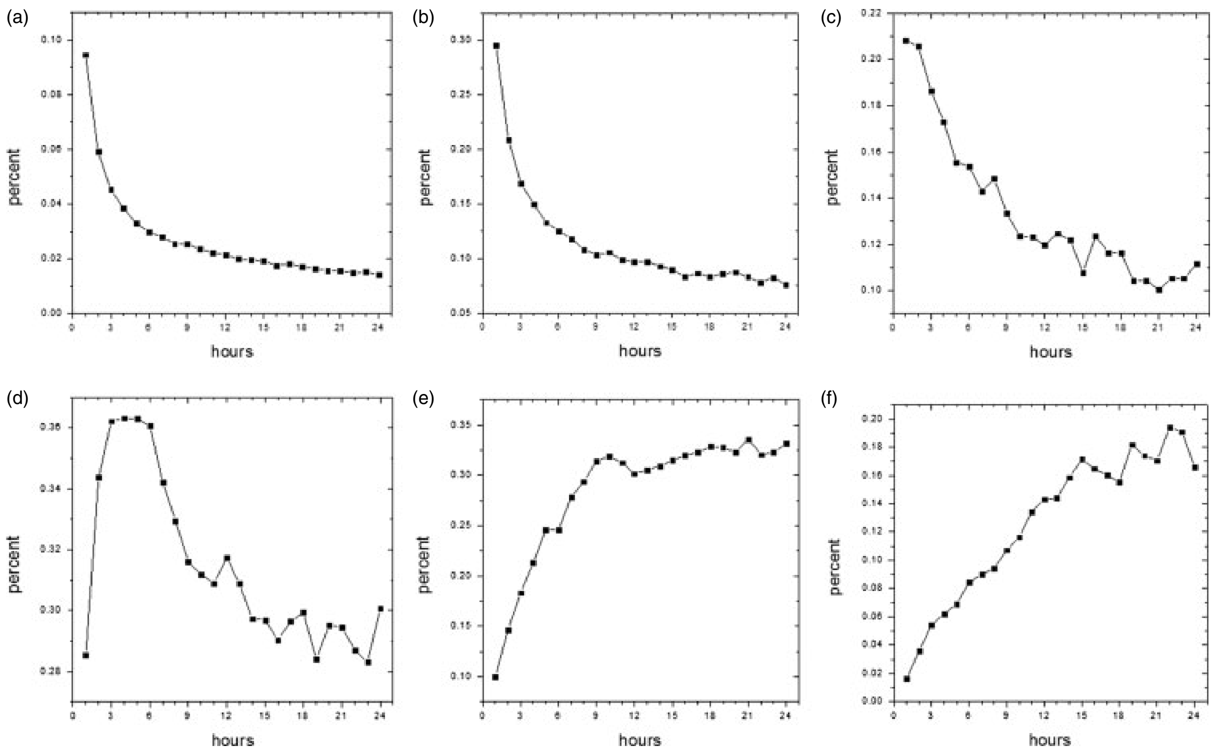

Figure 6. Percentage contributions of rainfall amounts of the 6 categories to the total rainfall amount in summer over Beijing Municipality (a) Slight (≤1 mm), (b) small (1.1–5.0 mm), (c) moderate (5.1–10 mm), (d) large (10.1–25 mm), (e) heavy (25.1–50 mm) and (f) torrential (more than 50 mm).

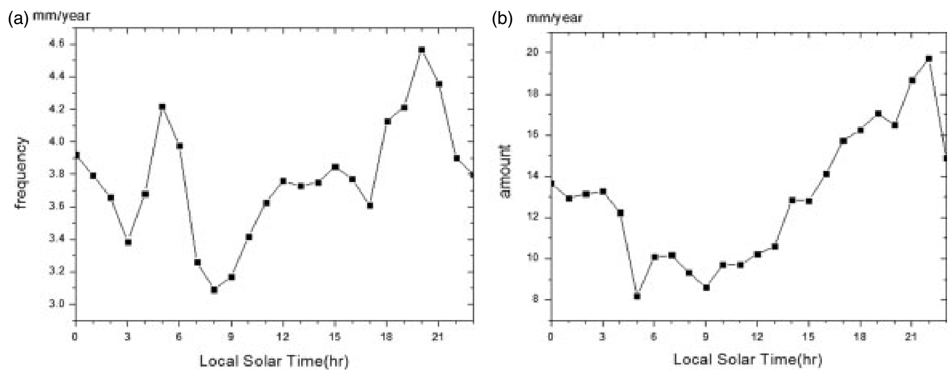

Figure 7. Diurnal variations of summer mean rainfall frequency (a) and rainfall amount (b) over Beijing Municipality.

for frequency appears in late night (0300–0500 LST), the stations in BJM mostly have the maximum rainfall frequency around 1900–2300 LST. The maximum time for summer rainfall amount is generally consistent with the maximum time for rainfall event frequency, but the rainfall amount in urban areas seems more concentrative in late evening, and the late night maximum for rainfall frequency is replaced by the early night maximum for rainfall amount in the southeast.

The propagation of the maximum time for summer rainfall frequency and amount from northwest to southeast might have been caused by complicated factors including local thermal instability, mountain-valley breeze, urban effect and land-sea breeze. It was suggested that phase shift between the land-sea breeze and mountain-valley breeze play a role in the spatial difference of rainfall maximum time over BJM,the phase of land-sea breeze is lagged behind the phase of the mountain-valley breeze by about 6 h (Liu *et al*., 2009a, 2009b), and this might have resulted in the occurrence of the late night maximum in the southeastern plain probably due to the influence by land-sea breeze circulation in summer.

For the minimum time of the rainfall event frequency and rainfall amount in a day, an obvious feature is that it mostly appears in morning (0600–0900 LST) over urban and central areas, in late morning over the northeast, and for rainfall amount in afternoon over some stations of the southeast. The morning minimum in urban areas might have been related to the weakest UHI intensity during the early morning, in addition to the influences from other local factors.

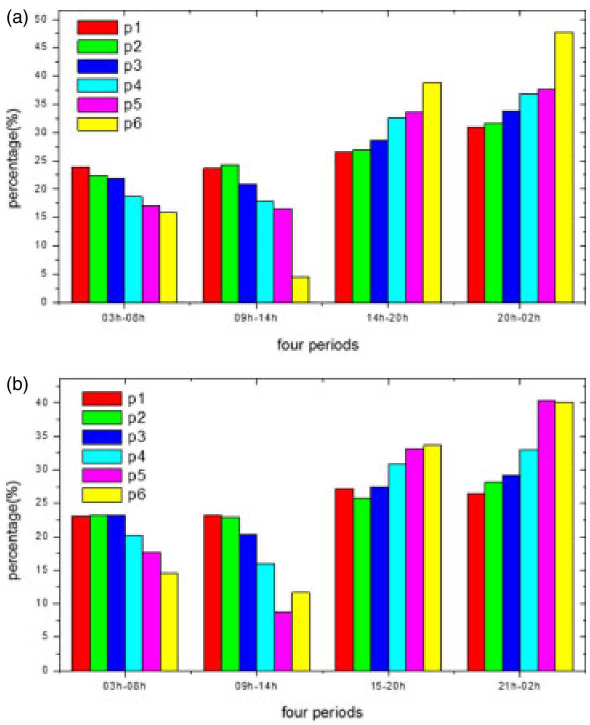

Figure 8. Averaged percentage contributions the six categories of rainfall events to the 24 h rainfall frequency (a) and rainfall amount (b) in summer over Beijing Municipality for four periods of hours in a day. P1: slight (≤1 mm), P2: small (1.1–5.0 mm), P3: moderate (5.1–10 mm), P4: large (10.1–25 mm), P5: heavy (25.1–50 mm) and P6: torrential (more than 50 mm). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

7. Discussions

Our analysis in this paper shows that the 1–3 h rainfall events obviously play the most important role in the rainfall duration and the contribution to the total rainfall amount over BJM, especially in urban areas. In a previous study by Wu *et al*. (2000), the authors had investigated the basic features of the short duration precipitation in BJM, which is valuable considering the available data in the earlier years. They could hardly describe the detailed feature of the precipitation in BJM, however, due to the limited observation data with merely five stations used around the urban area in 1996. In fact, sufficient observations of precipitation with enough length of records are extremely important for the study of spatial and diurnal characteristics of precipitation. In this paper, more densely distributed AWS observations (totally 123) for time period 2007–2010 is applied, and this enable us to reveal the climatological features of the diurnal variation and spatial distribution of the precipitation with fine-resolution over BJM. It is also notable that Wu *et al*. (2000) emphasized the short duration of precipitation, while this article focuses on the contribution of the rainfall events with different duration, including the short duration, in addition to the varied durations of precipitation. The conclusions drawn in our analysis are approximately in agreement with the study by Wu *et al*. (2000). Both revealed that the short-duration events are the most basic summer rainfall mode over BJM. The data of a much denser AWM network used in this study are making the results more convincing, and also enable it possible to reveal the more detailed spatial structure of the short-duration rainfall events.

In this article, we display the main characteristics of the diurnal variation of precipitation, showing the obviously larger values of rainfall frequency and rainfall amount between 2100 and 0500 LST, and the smallest values from 0500 to 1300 LST, with this feature being more notable for the hourly mean rainfall. Yin *et al*. (2011) also found a maximum between midnight and early morning in frequency of rain occurrence in Beijing when they analyzed the features of diurnal precipitation applying the data of 20 manual weather stations. Our analysis shows a more distinct diurnal cycle in daily total rainfall amount in terms of timing and magnitude of the variation, and we are also able to differentiate the summer diurnal precipitation variations of varied categories of rainfall in the study region.

The causes for forming the summer rainfall characteristics are complex. Many studies of urban climate were conducted for Beijing City, and these showed some basic features of SAT and precipitation. The UHI effect and the local UHI circulation might be an important factor for the observed spatial and diurnal variations of the frequency and intensity of summer rainfall in the urban areas of BJM. The spatial pattern of the percentage contributions of the short duration rainfall amount are obviously higher over the urban areas and the surroundings, e.g. and also the diurnal variations of the rainfall frequency and rainfall amount over the urban areas are more obviously characterized by a minimum in morning (0600–0900 LST) and a stable nighttime high values after 2100 LST. These might have been mainly caused by the UHI effect over the urban areas and the enhanced nighttime convective activity associated to the UHI circulation. Previous studies showed significant UHI effect and its increasing trend with time in Beijing urban sites (e.g. Ren *et al*., 2007; Liu *et al*., 2009a, 2009b). Our recent analysis based on the dataset of high-density AWSs further shows a distinct urban climatic feature with the UHI magnitude reaching a steadily high-value stage from 2100 to 0600 LST and a steadily low-value stage from 1100 to 1600 LST (Yang *et al*., 2012, pers. comm.). Furthermore, Sun and Su (2007) showed obviously increased precipitation in urban and southern suburban areas in winter and in urban and northern suburban areas in summer over the recent 30 years, and they attributed the changing pattern of seasonal precipitation to the enhanced UHI effect.

The mechanisms might mainly consist of the thermal effect, dynamic effect and retention effect of the urban boundary layer (Wu *et al*., 2000; Jiang and Liu, 2006). Surface air over the urban areas is warmed up by the UHI effect, which is conductive to the locally convective rainfall. In late evening and nighttime of summer, UHI effect and the UHI circulation can significantly strengthen the ascending motion of urban centre, increasing the unstable energy and the probability of rainfall occurrences in the

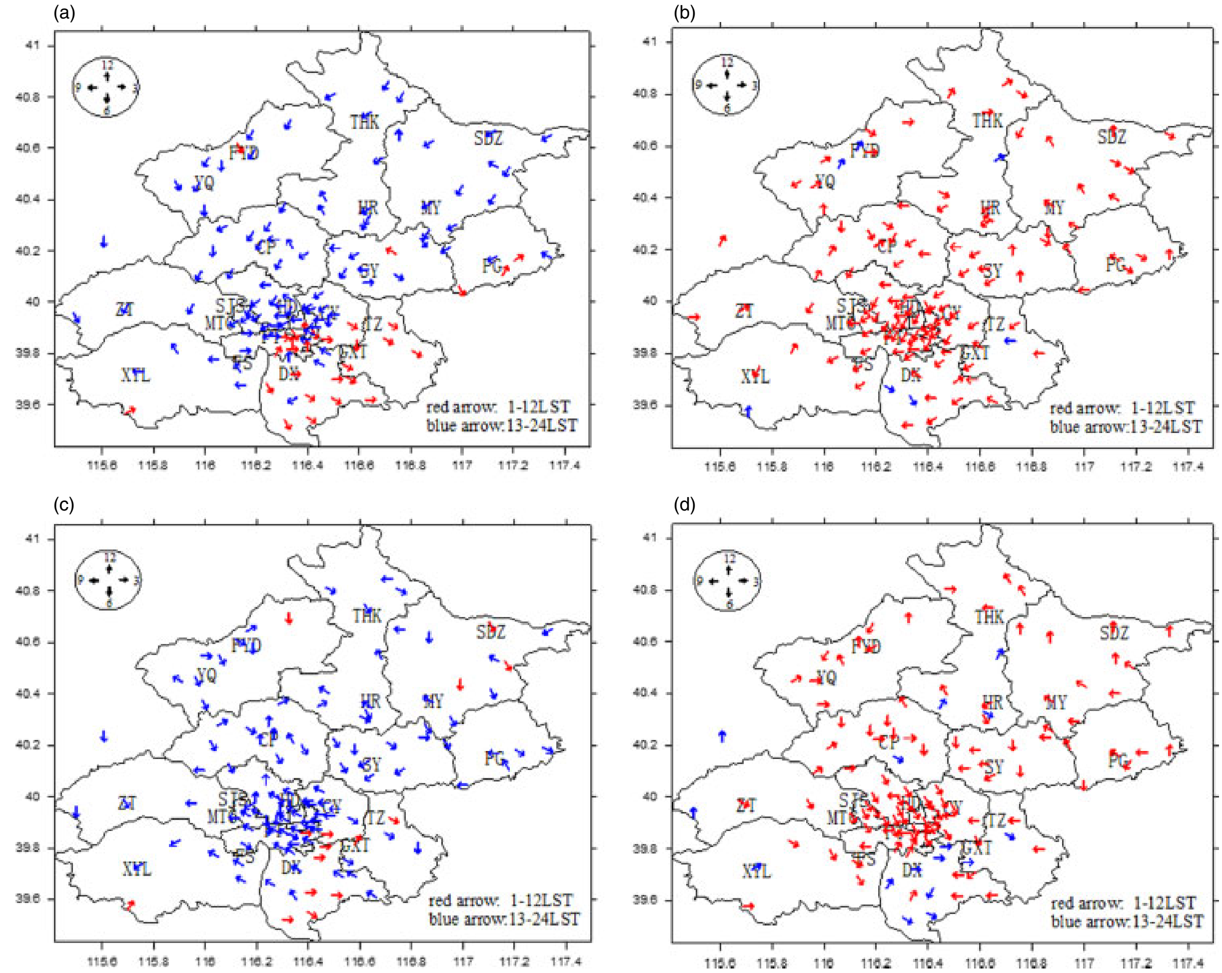

Figure 9. Spatial distributions of maximum and minimum time (LST) of summer diurnal rainfall variation. (a) Maximum for rainfall frequency; (b) minimum for rainfall frequency; (c) maximum for rainfall amount and (d) minimum for rainfall amount. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

urban centre and the surrounding areas. The rough underlying surface over the urban areas can also detain the rain-bearing weather systems longer, strengthening the short duration rainfall in certain extent (Hu *et al*., 2005).

8. Conclusions

An hourly rainfall dataset of 123 stations for period 2007–2010 is used in this article to examine the spatial and diurnal characteristics of summer rainfall in BJM. The main findings and conclusions are as follows.

1. The large accumulated rainfall duration in summer appears in the mountainous areas, with the stations near HR and MY registering the largest values of more than 200 h. In the plain areas of the southeast, the summer mean accumulated rainfall duration is usually less than 150 h. The large summer mean rainfall amount centres in the northeastern mountainous areas, and a marked large-value centre also appears in the northeastern part of the BJM built-up areas.
2. The summer rainfall events with duration less than 6 h contribute more than 50% of the total rainfall frequency and amount over BJM, indicating the importance of the short-duration rainfall events in the study region. The 1–3 h rainfall events obviously play the most important role in the accumulated rainfall duration and the total rainfall amount especially in urban areas.
3. The slight and small rainfall events ($\leq$5 mm an hour) take a large contribution to the total rainfall event frequency, while the heavy and torrential rainfall events (more than 25 mm an hour) contribute much less. For slight rainfall frequency, the relative contributions decease with the lasting time of the rainfall event. Small rainfall has a general decrease for the rainfall with lasting time less than 9 h, and an increase and large variability for the events with lasting time more than 9 h. The more intense hourly rainfall events are characterized by the marked rising frequencies with the lasting time, with moderate and large rainfall events undergoing an even more rapid increase between the lasting time of 1 and 6 h. There are seldom heavy and torrential rainfall events which actually occur within less than 3 h.

4. The relative contribution of slight rainfall to the total rainfall amount is very small, and large contributions come from large and heavy rainfall. For the rainfall events with less than 10 mm an hour, the relative contributions of rainfall decline rapidly with the lasting time within the first 3–9 h. However, the contributions increase rapidly at first and then come into a platform at 9 and 16 h for heavy rainfall events and torrential rainfall events, respectively.
5. The region-averaged 24 h rainfall frequency and amount rise to highest values around 2100 LST in evening and fall to lowest level around 0800 LST in morning. Although rainfall frequency has two peaks appearing respectively in early morning and later evening, only one peak develops in later evening for rainfall amount. The maximum and minimum of diurnal rainfall frequency are around 2000 and 0800 LST, respectively, while the maximum of diurnal rainfall amount appears at about 2200 LST and the minimum appears at about 0500 LST.
6. The percentage contributions of the six categories of hourly rainfall events to the total rainfall frequency and amount in BJM generally decrease with the increase in hourly rainfall intensity during 0300–1400 LST, but they usually increase with the increase in hourly rainfall intensity during 1500–0200 LST. Spatially, the maximum time for summer rainfall frequency, and in less extent for rainfall amount, propagates from northwest to southeast, with the northwest occurring in early evening, the central and southwest in later evening and the southeast in late night hours.
7. The diurnal variations of summer hourly rainfall in BJM is closely related to regional and local terrains, land use and land cover including urbanization, and the relative position of the sea and land. The mountainous areas of the west and north seem favourable to both short and long-duration rainfall in summer, and the main built-up areas form obvious centre for short-duration severe rainfall event. However, the mechanism for the summer diurnal rainfall characteristics in BJM is not known, and further study is needed in the future.

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