



Urbanization reduces frequency of light rain: an example from Beijing City

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Abstract

An hour precipitation dataset of 42 automatic weather stations is developed and applied to analyze the temporal and spatial characteristics of light precipitation in urban areas of Beijing City during 2007–2017. The stations are classified into three groups, including 18 sites in central urban area (4th Ring-Road, RR), 10 sites in peri-urban area (4th–5th RR), and 14 sites in suburban area (5th–6th RR). Light precipitation is defined as hourly rainfall of 0.1–0.3 mm. Analysis shows that light precipitation occurred in urban area the whole day, with the peak value in 0600 LST and minimum value in 1600 LST; monthly variation of light precipitation frequency (LPF) was characterized by the highest value in summer and the lowest value in winter; remarkable differences are found for the various urbanized areas, with the annual and seasonal mean LPF being generally small in central urban area and gradually increasing toward suburban area; the hourly mean LPFs during morning and nighttime are higher in summer than those in other seasons in each of the urban areas; relative humidity, aerosol, and wind speed might have been the major influential factors for the observed temporal and spatial pattern of light precipitation.

1 Introduction

Studies have shown that fast-speed industrialization and urbanization would modify the energy balance of cities at the surface level (Oke 1982; Kalnay and Cai 2003; Seto and Shepherd 2009; Ren and Zhou 2014). Meteorological elements such as temperature, precipitation, humidity, and wind in urban areas have been changed due to urbanization (Stewart and Oke 2012; Zhong et al. 2015; Yang et al. 2017a, b, c; Yang and Ren 2019). Precipitation in big cities draws more attention due to its key role in urban management, such as flash floods, waterlogging, landslides, and mudflows (Qian

et al. 2009a, b; Xing and Li 2019). More and more scholars have noted that urbanization has a crucial impact on precipitation and intense precipitation, especially in downtown and downwind areas of big cities (Changnon 1979; Han et al. 2014). Recent observational researches have supported the conclusion that precipitation tends to enhance over urban areas (Changnon et al. 1991; Rosenfeld 2000; Miao et al. 2010; Liang et al. 2011; Pathirana et al. 2014; Dou et al. 2015; Chen et al. 2015; Yang et al. 2017a, b, c). Numerical models were widely used to figure out the causes of precipitation amplifications in urban sites. The main causes can be summarized as such factors as urban heat island effect, surface roughness, and aerosol concentrations (Lin and Smith 1986; Thielen et al. 2000; Han et al. 2014; Ren et al. 2016).

The previous studies were mainly focused on the heavy rain events in urban area due to the potential damages. Storm bifurcation was first notified in New York City through radar by Bornstein and LeRoy (1990). Similar conclusions are drawn for some cities in India, Mexico, and China (Shastri et al. 2015; Carlos et al. 2015; Ren et al. 2016; Chen et al. 2009; Cutrim et al. 2000). Generally, the distribution and frequency of extreme rainfall events in different cities over the world have been changed because of the urbanization effect. It is well known that the typical character of precipitation is intermittent, which depends on temperature, moisture, and weather condition to a large extent. The regional climate

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changes or climate variability would also affect the precipitation in terms of pattern, intensity, frequency, and amount (Trenberth 2011). Take China as an example, more and more observations affirm that large variations of precipitation pattern occur in recent decades (Ren et al. 2015; Fu et al. 2008; Fu and Dan 2014; Gao et al. 2018). In addition to the increasing extremely intense precipitation events that lead to more damages and losses, the reduction of light rains is also remarkable across mainland China (Fu et al. 2014; Ma and Zhou 2015; Ren et al. 2015).

Light precipitation can be absorbed directly by soils to maintain soil humidity and to alleviate drought, and contributes more to the climatic and environmental change than heavy precipitation (Trenberth 2011). However, the light precipitation frequency was affirmed to be decreased over the last decades (Gong and Wang 2000; Liu et al. 2005; Fu et al. 2008). There are fewer rain days in recent years, but the daily precipitation intensity is on the rise (Zhai et al. 2005; Liu et al. 2005; Pendergrass and Hartmann 2014), most probably due to the decrease of light rain days (Qian et al. 2009a, b; Ren et al. 2015). Decreased light precipitation frequency has also been reported in Japan and India (Fujibe et al. 2005; Goswami et al. 2006). In China, a decrease of light rain days has been observed in many regions as well as in the country as a whole (Huang and Wen 2013; Li and Su 2014; Ren et al. 2015; Zhou et al. 2020). Change in temperature, aerosol concentrations, cloud, and relative humidity are examined to explain the possible reasons for light precipitation decrease, but no consensus has been reached (Huang and Wen 2013; Wu et al. 2016; Wen et al. 2016), though Ren et al. (2016) attributed the reduction to a combined influence of urbanization, aerosols, and measurement error.

Previous studies were focused on regional scale. Detailed comparison among different regions or between urban and rural areas is still lacking. Most of the researches were related to the long-term trends, while the diurnal variation characteristics of light rain were rarely analyzed (Huang and Wen 2013; Wen et al. 2016; Zhou et al. 2020). One of the main reasons is the lack of high-density observation records. On the other hand, a large number of automatic weather stations (AWSs) have been set up in China until the past several years, based on the operational standard issued by China Meteorological Administration (CMA). By 2017, a dense AWS network was finally built in Beijing area (Yang et al. 2017a, b, c; Yang and Ren 2019). About two-thirds of the stations attached to the network can provide hourly precipitation data.

The purpose of this paper is to examine the spatial and temporal variation of light precipitation in Beijing urban areas and the urban effects on light precipitation. Beijing urban areas are classified into three types for analyzing the different features of light precipitation in detail. The characteristics of precipitation in Beijing City were introduced firstly in Sect. 3.1. The main analysis was focused on the spatial and temporal characteristics of light precipitation in Sect. 3.2. Then, the difference of the

light precipitation among different areas was examined in Sect. 3.3. The causation of the light precipitation variation is briefly discussed before the conclusions are drawn.

2 Study area, data, and methods

Beijing Municipality, a high-density megacity covering about 16.4 thousand square kilometers, is located at the northern end of the North China Plain and in the south of the Yanshan Mountains. The flat southeast area occupies about 38% of the total area of Beijing, and the elevations are roughly below 100 meters above sea level. The north and west of Beijing are mainly mountainous areas. Climatologically, Beijing is characterized by a typical temperate continental monsoon climate, which is hot and humid in summer and cold and dry in winter. The rainy days and precipitation amount in Beijing are highly concentrated in summer (Jun-Jul-Aug), contributing to at least two-thirds of its annual total precipitation Yang and Ren (2019).

With accelerating urbanization, population in Beijing City experiences a dramatic growth and over half of the population settled in the urban areas. Along with the bewildering urban sprawl, a multi-RR system of transportation (including 4th, 5th, and 6th RRs, Fig. 1) has been developed in the urban regions (Yang et al. 2013). The zones inside different RRs actually represent different levels of urbanization with varied densities of city population and buildings.

The observed hourly rainfall amount data recorded by 56 stations inside the 6th Ring-Road from 2007 to 2017 are obtained from the Meteorological Information Center, Beijing Meteorological Bureau (MIC/BMB). The data have been preliminarily checked and quality-controlled by the MIC, and the possibly wrong records have been taken out by applying a regionally

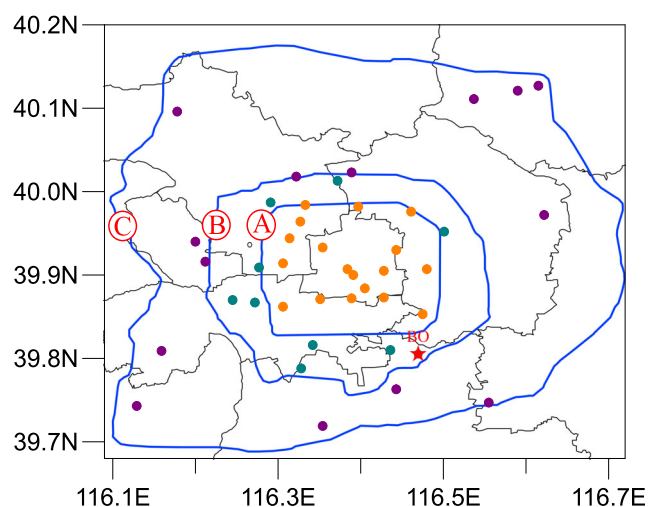


Fig. 1 Stations used in the Beijing urban areas as outlined by the 6th Ring-Road (blue solid circles, lines A–C respectively represent 4th RR, 5th RR, and 6th RR) and the typical observation station of Beijing (abbreviations of the station name is BO for Beijing Observatory)

climatological extreme value method. The data were confirmed to be accurate in the previous studies (Yang et al. 2013). The stations with too many erroneous records have been ruled out from the dataset directly, and the methods of threshold values and manual identification are also applied in checking. Based on the observational records and the precipitation features of Beijing, different seasons have been given different threshold values (50 mm/h for spring and autumn, 80 mm/h for summer, and 30 mm/h for winter). Each hourly record above its seasonal threshold is checked and then is adjusted if proved wrong by comparing the records of nearby stations. Only those sites with missing values less than 3% of the total records for the 11 years are selected for use, in order to minimize the influence of missing records on the analysis. Additional description of quality-control techniques was reported in detail by Yang et al. (2013). After the quality control, 42 observational stations inside the 6th RR are used (Fig. 1) eventually.

To figure out the urban effects on light precipitation among the distinct sites of the built-up areas, all the selected urban stations are geographically classified into three groups: those inside the 4th RR or central urban area (composed of 18 stations), those between the 4th–5th RRs or peri-urban area (composed of 10 stations), and those between the 5th–6th RRs or suburban area (composed of 14 stations). The RR loops well represent the different boundaries of varied urbanized zones at present, and also the boundaries of urban-rural zones in different time periods, in Beijing (Mu et al. 2012). The densest and tallest buildings and almost all the central commercial areas concentrate within the 4th RR.

In the study, the hourly precipitation is defined as rain record equal to or more than 0.1-mm precipitation amount accumulated during an hour. In the previous studies, light precipitation is generally regarded as 0.1–10 mm (Zhou et al. 2020) based on daily precipitation data, but a clear definition of light rain based on hourly precipitation is rare. Considering the feature of Beijing precipitation, light precipitation in this paper is defined as an hourly rain record with 0.1–0.3 mm. The light rain as defined in this paper contains the slightest portion of the daily precipitation-based light rain.

Due to the slight accumulated amount of light precipitation, the statistic result of precipitation reveals that the feature of light precipitation amount is in accordance with its occurrence. This paper mainly analyzes the feature of the light precipitation frequency (LPF) in order to unravel the general pattern of the category of hourly precipitation in Beijing urban and suburban areas. For each site, the annual/seasonal/monthly mean LPF is the total number of precipitation hours per year/season/month. Besides, in order to compare the results of different areas, the average values of LPF of those sites inside each of the zones are also calculated.

3 Results

3.1 Characteristics of total precipitation

An overview of the characteristics of precipitation in Beijing City is helpful for studying light precipitation. In Beijing, most rainfall events occur in warm seasons, especially in July and August. We calculated the annual mean frequencies and amounts of precipitation of each site inside the 6th RR, as shown in Fig. 2 a and b.

The distributions of annual mean frequencies and amounts of precipitation are different. There are at least three high-value zones in the frequency map, scattering in urban center and its northwestern and northeastern parts. The largest mean frequency of more than 370 h per year is registered at Zi Zhu Yuan (ZZY) station. In the southern areas farther from urban center, the mean frequencies are usually less than 290 h per year. The distribution of annual mean rainfall amount (Fig. 2b) is more consistent with the divergent expansion of built-up areas and transportation system. The annual mean amount of precipitation in the study region is 584 mm, which is a bit higher than the average rainfall amount (561.5 mm) over the whole Beijing Municipality. An obvious high-value center appears in the eastern part of central urban area, with Si Hui Qiao station surpassing 680 mm. The northwestern parts witness the lowest mean precipitation amounts, generally less than 520 mm, and the lowest center appears in Dao Xiang Hu (DXH). Our previous study of urban heat island (UHI) showed a negative UHI intensity at this station (Yang et al. 2013). The sparser buildings and negative UHI might be one of the reasons for the lowest amount of precipitation.

3.2 Characteristics of light precipitation

Figure 3 shows the diurnal (Fig. 3a) and monthly (Fig. 3b) cycle of LPF over the study areas. Overall, light precipitation occurred in each hour the whole day. For the study period, an early morning maximum (0600 LST) of 5.6 times is seen in the mean value of LPF. The secondary maximum value occurs at 1100 LST. The minimum of LPF appears during the afternoon (1600 LST) at a value of 3.7 times. The standard deviation (SD) of each hour in day and night has no significant difference. The maximum value of SD (1.21 times) is observed around 0600 LST, which coincided with the time of peak mean frequency. The minimum value of SD (0.66 times) occurs around 2200, which is different from the valley time (1600 LST) of LPF. The diurnal variation of light precipitation amounts and their standard deviations are almost as same as frequency (not shown). The average amount of light precipitation in a day is 0.60 mm, with a peak of 0.73 mm and a valley of 0.50 mm. Late morning at 1100 LST can be considered as a dividing point, with a high level of LPF dominant before 1100, especially from 0200 to 1100 LST, and a low

Fig. 2 Spatial distribution of annual mean values of hourly precipitation frequency (a) and amounts (b) in urban areas

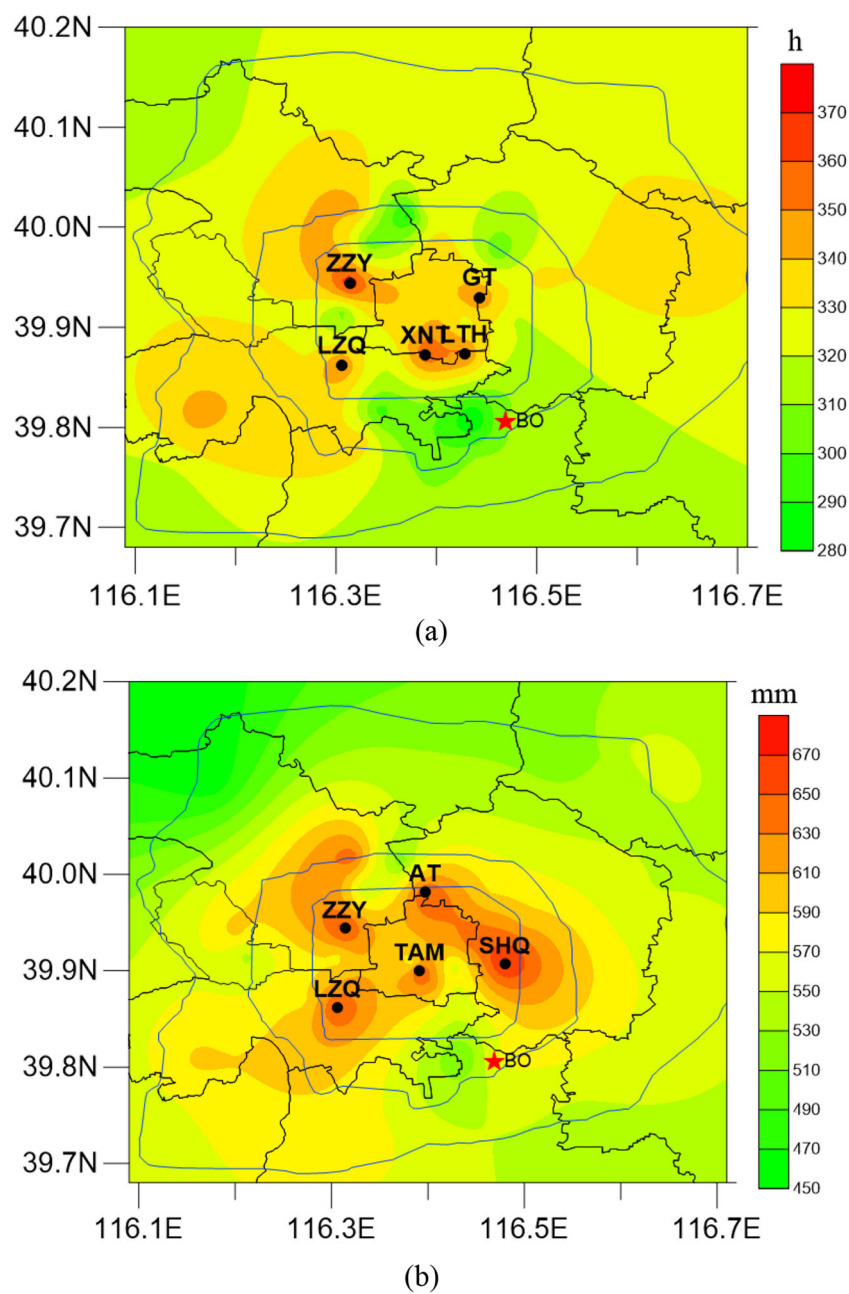
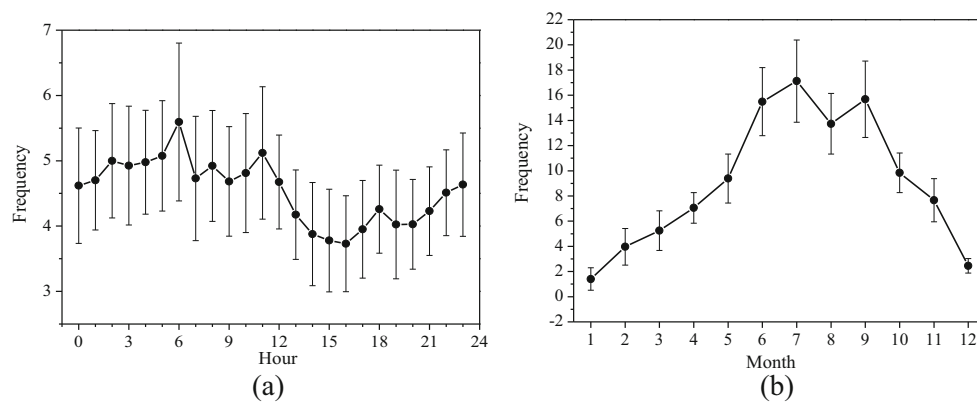


Fig. 3 Diurnal (a) and monthly (b) variations and their standard variations of light precipitation frequency in Beijing urban areas



level of LPF prevailing after 1100, particularly during the period of afternoon (1300–1700 LST).

It is notable from Fig. 3b that monthly variation is in accordance with the climatological feature of precipitation over Beijing. The average monthly value of LPF is 9.1 times. In summer, LPF has high values of 15.5 times, while the low occurrence of 2.6 times is in winter. The monthly curve shows the peak value of LPF in July (17.1 times), accounting for 36.9% of all. Additionally, values in July and September are higher than those for the rest of the months, the sum of which accounts for about 67.0% of all light precipitation of the whole year. It is interesting to note that the monthly mean value of LPF in August is not the largest during the summer period, with a mean value of 13.7 times, about 2 times lower than that in July or September. The minimum value appears in January with only 1.4 times. Standard deviations of each month are closely related to the monthly mean value of LPF. SD is higher in summer but lower in winter. The convective heavy precipitation mainly happens in summer, and the rainfall has a larger temporal and spatial variability and higher SD as compared to that in winter.

The spatial distribution of annual mean LPF is shown in Fig. 4. The regional average annual mean LPF is 109 times. The maximum LPF center (134.2 times) appears in the northeastern part of the urban areas. The other two large LPF centers are both located in the western part. It is obvious that all high LFP centers are in suburban area. The station with minimum LPF (83 times) is Yu Yuan Tan (YYT), which is located in a small park in the northwest of the urban center inside the 4th RR, surrounded by dense buildings and several expressways.

In general, the distribution of LPF seems to be closely related to urbanization. The more urbanized a site is, the lower the value of the LPF. However, there are a few exceptions. An obvious relatively higher center occurs at the central area (Fig. 4), with three stations registering the annual mean LPF of 124.4, 123.8, and 122.9 times respectively. The site named

Tian An Men (TAM) is next to Tian An Men Square, which is probably the most spacious urban square in the world. The other two stations are both in parks, surrounded by more grass, trees, and water. The common feature of the three sites is that their surroundings are open and spare, being similar to the sites relatively far from urban center.

Figure 5 shows the spatial distribution of seasonal mean LPF. There is a significant difference among seasons. The mean LPF is much larger in summer than that in any other season. The average value in summer is 46.3 times, accounting for 42.5% of the whole year. During the period, the seasonal mean LPF shows a considerable reduction toward suburban area, with 40 times isotherm covering most sites in central urban area. Spring and autumn register the moderate mean LPFs, with average values of 21.7 times and 33.2 times respectively. However, there is an apparent difference between them. Although the LPFs of sites away from urban center are relatively higher in spring and summer, they are not the highest ones. In spring, the maximum value of LPF (29.1 times) occurs in Yun Gang (YG), which is in the south-western part of the suburban area, while the largest value (51.1 h) in summer is recorded by Lou Zi Zhuang (LZZ) in the northeastern part of the suburban area. The lowest center of spring and autumn is also different. The minimum value of a site in spring is at JG near the south 5th RR, while the lowest value in autumn is at Si Hui Qiao (SHQ), the western part of the central area. Besides, the central urban area also undergoes an opposite change between spring and autumn. There is a small center with high values in spring, while it does not appear in autumn. The seasonal mean LPF has the lowest value in winter, with most areas less than 8 times. Interestingly, sites with winter mean LPF more than 10 times are all in central urban area, which shows a completely opposite pattern to other seasons.

It is easily understandable that the annual and seasonal mean LPF is at the highest in the suburban area and the lowest in the central urban area among the above three areas. Suburban (central urban) area is characterized by a lower (higher) condensation level during nighttime and a larger (smaller) relative humidity all the hours of a day Yang and Ren (2019), leading to the highest (lowest) LPF due to the shorter (longer) distance for raindrops to travel and less (larger) evaporation. The higher concentration of aerosols in central urban area may also contribute to the lower LPF as compared to the suburban area. The high mean LPF in winter in central urban area might have been related to the stronger UHI intensity which leads to stronger convection.

3.3 Comparison among different zones

Figure 6 shows the annual mean diurnal LPF variation in the three urban areas. The standard deviation of each area is also given in the figure. It is obvious that there is a common diurnal

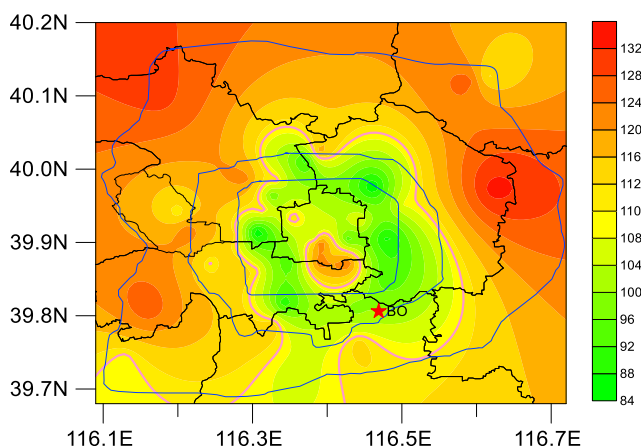


Fig. 4 Spatial distribution of annual mean frequency of hourly light precipitation in Beijing urban areas during 2007–2017

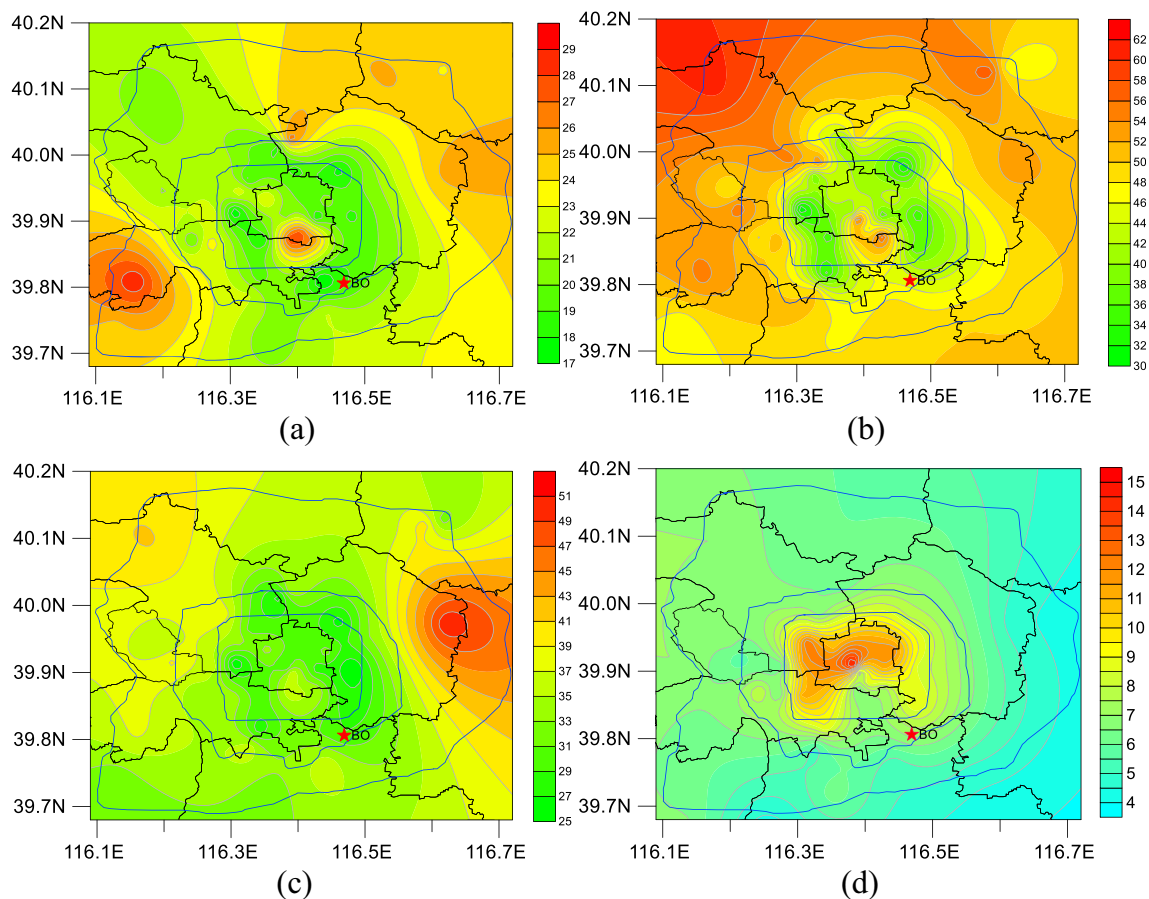


Fig. 5 Spatial distribution of seasonal mean values of hourly light precipitation in Beijing urban areas during 2007–2017 in spring (a), summer (b), autumn (c), winter (d)

variation pattern among the three areas, which is similar to the diurnal cycle of the whole area. However, there are significant differences among the urban and suburban areas.

The first feature is that, the greater the urbanization, the lower the average LPF. The regional average annual mean LPF is 4.33, 4.35, and 4.84 times in central urban area, peri-urban area, and suburban area respectively (Table 1). Annual

mean LPF difference between central urban and peri-urban areas is not significant. However, the annual mean LPF in night time during 2200–0500 LST in central urban area is significantly smaller than that in the peri-urban area. Daytime (0600–1800 LST) can be divided into two stages of morning (0600–1100 LST) and afternoon (1200–1800 LST). In the morning, the annual mean LPF in the central urban area is larger than that

Fig. 6 Diurnal variation of annual mean value of LPF in different regions over Beijing urban area during 2007–2017

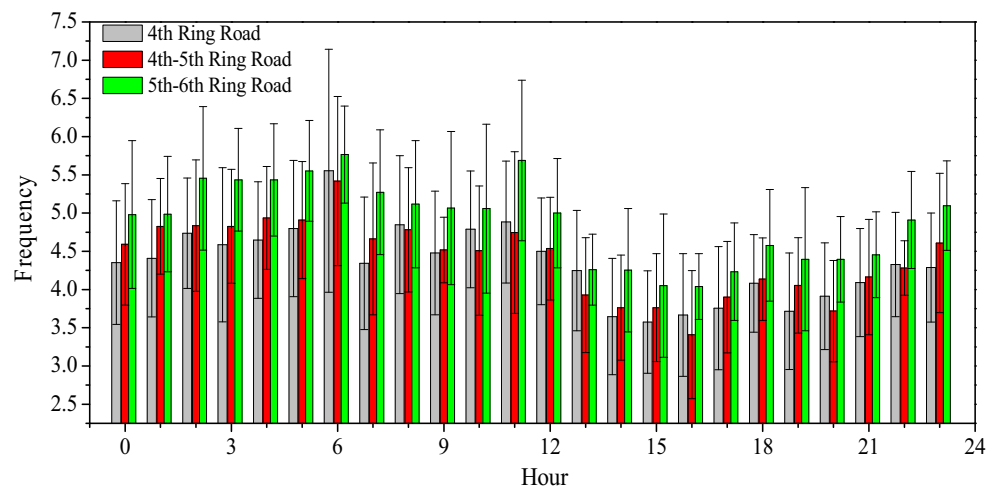


Table 1 Statistical features of daily LPF among different urban areas in Beijing City during 2007–2017.

		4th RR	4th–5th RR	5th–6th RR
Areal mean value		4.33	4.35	4.84
Standard deviation		0.81	0.75	0.76
Daily peak	Value	5.56	5.41	5.77
	Occurrence time	0600	0600	0600
Daily valley	Value	3.58	3.41	4.04
	Occurrence time	1500	1600	1600

in the peri-urban area except for 0700 and 0900 LST. However, the afternoon stage shows an opposite pattern. The value of daytime LPF in the central urban area is more likely to be lower except for 1300 and 1600 LST, while the annual mean LPF in daytime in the peri-urban area is larger.

Early morning from 0200 to 0600 LST is characterized by a lower condensation level in all areas and a stronger UHII in central urban area, and this would be the main reason for the highest LPF in particular in central urban area. Similarly, the hourly LPF remains relatively low from 1300 to 1700 LST, because of the largely heightened condensation level, a weaker UHII, and the lower relative humidity or large vapor pressure deficit, compared to the suburban area, during this time of the day.

Figure 7 shows the monthly mean LPF and standard deviation in the three urban areas. The regional average annual mean values of LPF are 8.69, 8.82, and 9.79 times in the central urban area, peri-urban area, and suburban area respectively (Table 2). The maximum values in different zones all appear in June, and all of the minimum values are in January. It is also noted that, in wet seasons, the seasonal transitions are more abrupt and variable than those in dry seasons. The period from June to September is peak stage of light precipitation amount. The period from November to March is also noteworthy, because the monthly mean LPF in 4th RR during this period is greater than that during the other periods of the year.

Table 2 Statistical features of monthly LPF among different urban areas in Beijing City during 2007–2017

		4th RR	4th–5th RR	5th–6th RR
Areal mean value		8.69	8.82	9.79
Standard deviation		1.81	1.75	1.46
Daily peak	Value	15.6	17.0	19.2
	Occurrence month	7	7	7
Daily valley	Value	1.97	1.07	0.91
	Occurrence time	1	1	1

It also has a lower variability. Due to the rare occurrence of LPF, the disparities among the three urban areas and the standard deviations remain small during the cold season.

Figure 8 presents the hour-month plots of the LPF averaged for the different urban areas for the period 2007–2017. The detailed comparison generally confirms that the hourly mean LPF during morning and nighttime is higher in summer than that in other seasons in each urban zone. Nevertheless, higher daytime LPF in August is less obvious within the above areas. Once again, considerable differences exist among the different urban areas. In the suburban area, the hourly mean LPF can reach as high as 1.04 times during the early morning stage in July, approximately 0.95 times higher than that in the afternoon stage of December. By contrast, the maximum LPF in the central urban area is 0.91 times, happening around 2100 LST in July, and the relatively larger LPF periods among summer months in this area are also different. For example, the large LPF period in July is in early morning (0500–0800 LST) and late evening (2100–2200 LST), while the peak stage in September is from 0200 to 0600 LPF, 2 h earlier than that in July, and the values at nighttime are not so notable. Between the 4th and 5th RRs, high LPF values in summer are relatively stable, prevailing in early morning (0200–0700 LST), and even a few secondary high values are registered in the evening (1800–2100 LPF) in June.

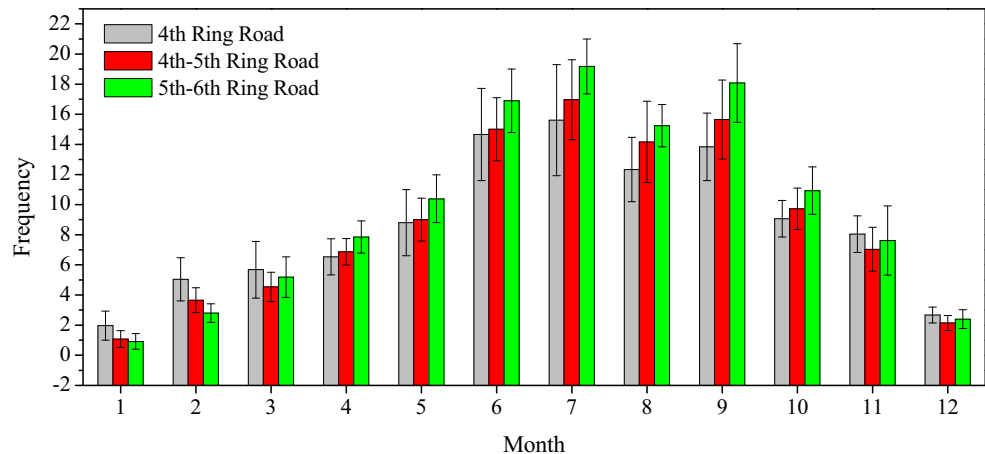
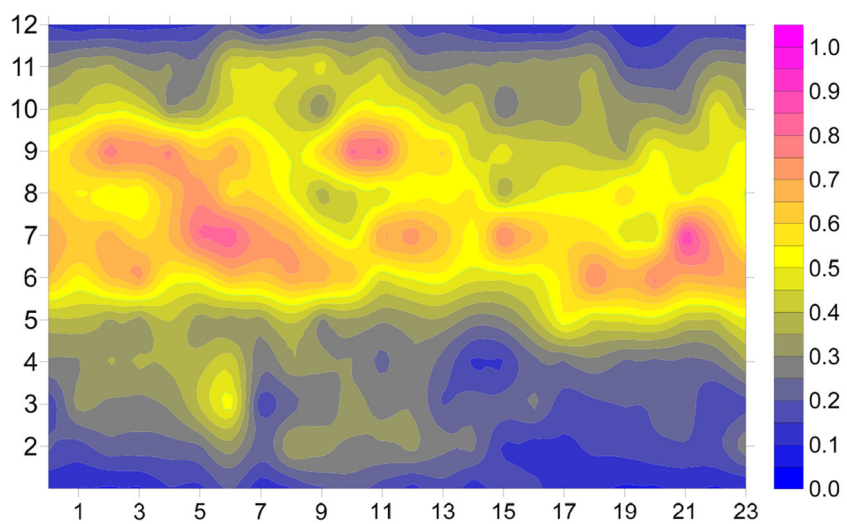
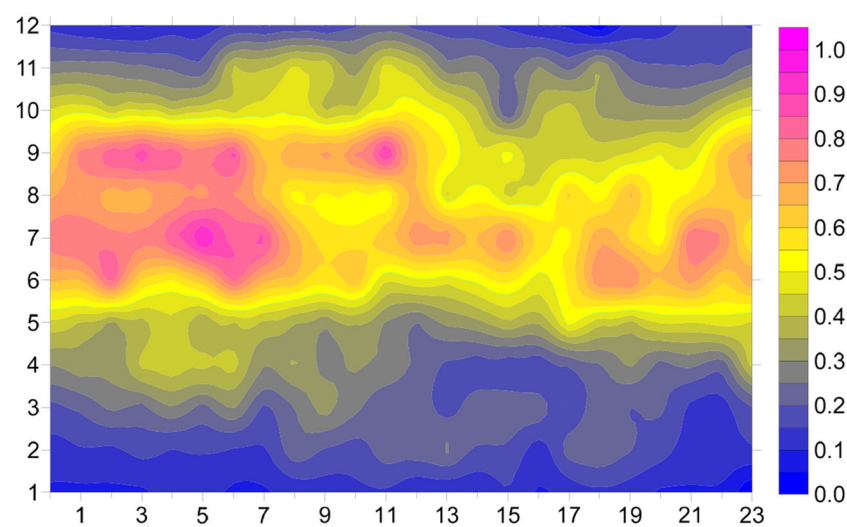
Fig. 7 Monthly variation of mean value of LPF in different urban areas in Beijing City during 2007–2017

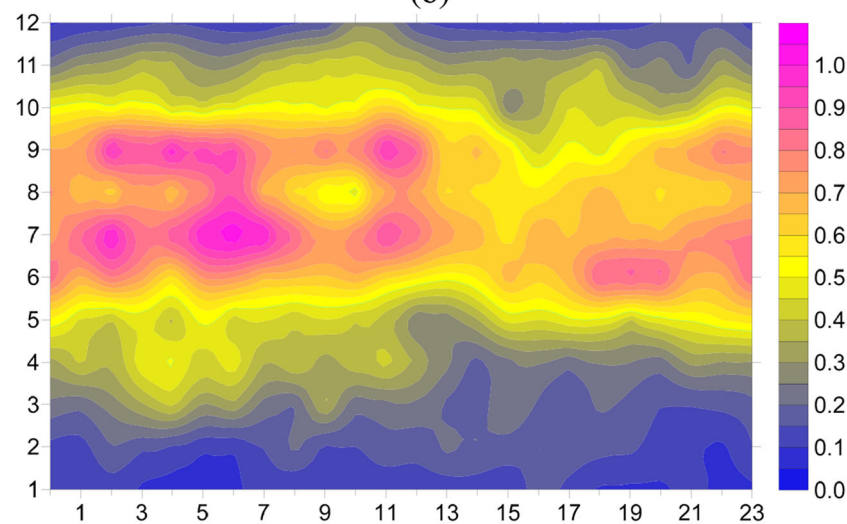
Fig. 8 Hour vs month plots of the LPF averaged for the different urban areas for the period 2007–2017. Isolines of 0.5 times are marked with blue



(a)



(b)



(c)

4 Discussion

Although the amount of light precipitation accounts for only 2.5% of the total precipitation in Beijing urban area, the light precipitation frequency (LPF) accounts for 33.3% of the total rainy hours per year. As one of the major types of hourly precipitation events, the in-depth understanding of temporal and spatial characteristics of light precipitation, and the urban effect on the light precipitation process, is scarce and insufficient.

Table 3 and the above analysis show that the light precipitation seems to be less in both frequency and amount in more urbanized areas. This indicates that urbanization has changed the pattern of precipitation. Similar conclusion has been found in previous studies, which were mainly focused on heavy or extreme rainfall events (Chakravarti and Archibold 2008; Robert 2010). Combined with the previous observational studies (Yang et al. 2013; Yang et al. 2017a, b, c; Yang and Ren 2019; Yan and Yang 2000), the possible influence of urbanization on LPF in Beijing urban areas could be discussed as follows.

LPF, light precipitation frequency; *TPF*, total precipitation frequency; *LPA*, light precipitation amounts; *TPA*, total precipitation amounts

Studies show that the relative humidity of low-layer atmosphere was closely related to light precipitation (Ren et al. 2016; Zhou et al. 2020). Yang et al. (2017a, b, c) found that, in urban area of Beijing, especially in urban center, the relative humidity is apparently lower than that in the sites outside building-up area, forming remarkable urban dryness island effect. The feature of relative humidity distribution inside the 6th RR of Beijing City is well in accordance with the spatial distribution of LPF shown in Fig. 5.

The mechanism of relative humidity influence could be summarized as follows. Firstly, the low relative humidity and large saturation vapor deficit in the boundary layer would facilitate the evaporation of some tiny droplets, well before they fall down to the ground. Secondly, the surroundings of rain gauge in urban area differ from those in rural regions. Lower relative humidity and higher surface air temperature promote evaporation of the in-gauge water, which may affect the collection and reading of light precipitation. Thirdly, due to urban heat island effect, the condensation layer heights would rise up in urban area, leading to a higher cloud base height (Fig. 9). The higher cloud base height could extend the dropping distance of droplets and would make them more likely to vaporize before reaching the ground (Ren et al. 2016).

Aerosol was regarded as an important factor affecting precipitation (Williams 2002; Qian et al. 2009a, b; Wu et al. 2017; Ramanathan et al. 2001; Rosenfeld et al. 2007). If there is not enough water vapor, the aerosol as extra condensation nuclei cannot bring precipitation (Rosenfeld 2000; Stevens and Feingold 2009; Storer et al. 2010). In urban areas, more pollutants have been emitted by human activity, but the water

vapor is not enough, thus the precipitation is less possible compared to the rural areas (Ren et al. 2016). A sketch of the combined influence of aerosol effects and UHI is shown in Fig. 9.

Wind speed is also likely to affect the veracity of the light precipitation records. The higher wind speed may increase the possibility of record error because the catch rate tends to decrease (Ren et al. 2016). Our previous studies Yang et al. (2013) have reported a lower wind speed in urban center, and the difference between urban and rural area is more significant in spring and winter. In this paper, the monthly variation of LPF among different urban areas shows that the LPFs from November to April in central urban area are a little higher compared to the record in the other urban areas. This might have been related to the stronger urban stilling effect in the urban center, which leads to a higher catch rate of gauge and a larger frequency and amount of light precipitation. It is possible that a few stations within the 4th RR also record significantly larger annual mean LPF due to the weakened surface wind speed caused by the surrounding buildings, and a few others observe the smaller LPF probably due to the relatively stronger wind speed in an open ground.

Although the spatial difference of light precipitation is detectable partly because of the varied wind surrounding, the general conclusion that annual and seasonal mean light precipitation frequency, except for winter, will decrease in more urbanized areas is not changed. Urbanization has exerted a significant influence on the temporal and spatial pattern of light precipitation in Beijing City.

By analyzing the relation of light rain and urbanization, therefore, this paper reveals that precipitation changes spatially in the areas of Beijing City, and light rain frequency is more sensitive to the level of urbanization. It is possible that the impact of urbanization on light rain frequency in urban areas is likely to intensify with the fast expansion of big cities, not merely in China, but also in other regions of the world, and certain measures may need to be taken to adapt to the change of precipitation pattern in urban areas, in addition to the increase of intense precipitation due to the combined influence

Table 3 Annual mean of LPF and LPA and the proportion in annual total precipitation

	4th RR	4th–5th RR	5th–6th RR
Annual mean LPF	104.2	105.9	117.5
Annual mean TPF (mm)	334.1	316.3	325.4
Proportion	31.2%	33.5%	36.1%
Annual mean LPA	14.13	14.0	15.3
Annual mean TPA (mm)	611.5	574.7	555.1
Proportion	2.31%	2.43%	2.76%

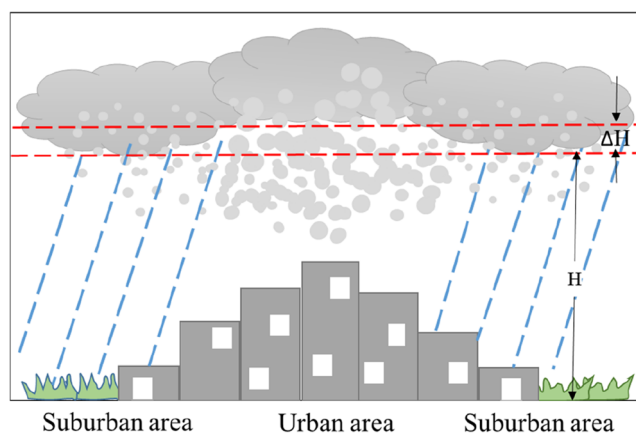


Fig. 9 A sketch of aerosol and UHI influence on LPF in Beijing urban areas. Dashed red lines indicate condensation heights in suburban (H) and urban ($H+\Delta H$) areas, grey circles indicate larger rain droplets, and dashed blue lines indicate small droplets

of urbanization and global climate change (Ren et al. 2016; Yang and Ren 2019).

The findings reported in this article are also helpful for deepening our understanding of urban precipitation structure and the effect of urbanization on local climate, and for the evaluation and adjustment of urban bias in the observational data used for detecting regional and global climate change. Obviously, they provide a key clue to the unsolved question on causes of the long-term decrease of light precipitation observed in many regions of the world over the last decades.

5 Conclusions

This article applied an 11-year ground-based hourly precipitation dataset to analyze the characteristics of light precipitation among different urbanized areas of Beijing City. Overall, the analysis reveals that the spatial and temporal pattern of light precipitation is highly related to urbanization. The main conclusions are as follows:

- (1) The annual mean values of LPF in central urban areas or nearby areas tend to be small, and those in the suburban area are significantly larger.
- (2) The seasonal mean LPF is larger in summer than that in any other season. Summer also witnesses the most obvious feature of small values in urban center, while an opposite pattern is seen for winter.
- (3) The light precipitation occurs in urban area the whole day, with the peak value in 0600 LST and minimum value in 1600 LST; hourly mean LPFs during morning and nighttime are higher in summer than those in other seasons in each urban area.
- (4) Lower relative humidity, higher aerosol concentration, and smaller wind speed might have been the major

influential factors for the observed temporal and spatial pattern of light precipitation in Beijing urban areas.

Data and materials availability The code, data, and material used in the current study are available from the corresponding author on reasonable request.

Author contribution Ren raised the questions and designed the study. Yang performed the data analysis and completed the manuscript. Yan and Deng assisted in processing data and drawing the figures.

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Declarations

Ethics approval Not applicable.

Consent for publication The authors agree to publication in Theoretical and Applied Climatology.

Conflict of interest The authors declare no competing interests.

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