Article ID: 1006-8775(2019) 03-0414-07

DIURNAL VARIATIONS OF SUMMER PRECIPITATION IN SHANGHAI

HOU Yi-ling (侯依玲)[1,2], CHEN Bao-de (陈葆德)[3]
(1. Nanjing University of Information Science & Technology, Nanjing 210044 China; 2. Shenyang Regional Climate Center, Shenyang 110166 China; 3. Shanghai Typhoon Institute, China Meteorological Administration, Shanghai 200030 China)

Abstract: This paper investigates the diurnal variations of summer precipitation in Shanghai by using the city's hourly precipitation data over a span of 35 years. The result shows that the precipitation peaks twice, i.e., in the morning and in the afternoon. Precipitation in the morning is characterized by light to moderate rain, and that in the afternoon by heavy to super heavy rain. The peak of short-duration precipitation is mostly found in the afternoon and at dusk, and that of long-duration precipitation in the morning. Most of the precipitation events in Shanghai are of a short duration of 2-3 hours. Basically, the precipitation is spatially distributed in three areas: the eastern coastal and central urban area, where the precipitation peaks mostly in the afternoon, the southern coastal area, where the precipitation peaks both in the afternoon and during the night, and the western area, where long-duration precipitation accounts for a much larger proportion than the other two areas.

Key words: diurnal variation; summer precipitation; climate pattern; Shanghai
CLC number: P435 **Document code:** A
doi: 10.16555/j.1006-8775.2019.03.012

1 INTRODUCTION

Diurnal variations of precipitation are an important metric to describe regional climate pattern. Scholars have conducted numerous studies on the global and regional patterns of precipitation such as frequency, intensity and persistence[1-6]. Using the precipitation data automatically collected for the period from 1991 –2004 by meteorological stations across China, Yu et al.[7, 8] became the first to analyze the diurnal variations of summer precipitation in the Chinese mainland. The analysis revealed that the diurnal variations of summer precipitation in China vary significantly by region: the precipitation of the middle reaches of the Yangtze River peaks in the early morning, and that of the Jianghuai and Huanghuai areas peaks twice, i.e., in the morning and in the afternoon. Their study also concluded that precipitation persistence is the key factor for distinguishing the two diurnal variation phases of precipitation in east China. Zhou et al.[9] validated this conclusion by using the metrics of precipitation frequency and intensity, while finding that satellite data can only be used to capture the afternoon peak of the diurnal cycle of precipitation in the Jianghuai region. In their recent study on the diurnal variations of precipitation in eastern China during the warm season (from June to September), Yuan et al.[10] found that the change in the early morning peak is closely associated with how the east Asian summer monsoon rainband changes.

Further researches have been conducted on the diurnal variations of precipitation in different regions of China. Li et al.[11] found that Beijing experienced a sharp decrease in long-duration precipitation and a continued increase in short-duration precipitation over the period from 1961 to 2004. In their analysis of the summer precipitation of the same period in the Hai River basin, Yin et al.[12] presented that short-duration precipitation accounted for an increasingly large proportion of the total precipitation in this area. Based on the metrics of precipitation amount, intensity and frequency, Zhou et al.[13] analyzed the diurnal temporal and spatial variations of summer precipitation in Shandong from 1996 to 2008. Similar methods were applied by Tang et al.[14] and Dai et al.[15, 16] to study diurnal variations of precipitation at the regional scale. These studies can be a helpful addition to the future research of diurnal variations of precipitation and their formation mechanisms. Because of the accuracy and continuity of the data, these works are limited in the study of urban-scale climate which requires higher spatial resolution and longer time.

Surrounded by the East China Sea to the east and the Hangzhou Bay to the south, Shanghai is located at the estuary of the Yangtze River and joins the other parts of the Chinese mainland to the west. An economically developed city, Shanghai has been the No.1 GDP contributor in China in past 10 years. As the largest estuarine city along the coastline of China, Shanghai has

Received 2019-01-23; **Revised** 2019-05-06; **Accepted** 2019-08-15
Foundation item: Climate Change Special Fund (CCSF201526, 201609, 201910); Research Innovation Plan for Graduate Students in Jiangsu Universities (CXZZ12_0497)
Biography: HOU Yi-ling, Ph. D. Candidate, Senior Engineer, primarily undertaking research on climate change impacts.
Corresponding author: CHEN Bao-de, e-mail: baode@typhoon.org.cn

been significantly impacted by the urban heat island effect as a result of rapid urbanization. Meanwhile, the action of the land-lake breeze from the Taihu Lake and the sea-land breeze puts the city under a special zonal secondary circulation system, which renders the distribution of precipitation largely uneven in Shanghai. This paper studies the diurnal variations of summer precipitation in Shanghai using the city's hourly precipitation data across a span of 35 years. The aim is to provide deeper insights into the diurnal variations of precipitation at a city level, and to support improvements in numerical models. The conclusions are expected to inspire the development of design and construction standards for urban roads and drainage networks in Shanghai.

2 DATA AND METHODS

Data used in the study comes from the Shanghai meteorological observation network, which was first established in the 1950s and completed in around 1960 to cover all the 11 districts and counties of Shanghai. Specifically, the study employs the hourly precipitation data collected in the form of reports from the 11 meteorological stations of this observation network over a 35-year period from 1981–2015 for season June-August.

Figure 1 shows the distribution of mean summer precipitation in 1981 –2015 and the 11 meteorological stations. As shown in the figure, the mean summer precipitation across Shanghai over the 35-year period is 501.8 mm, with a maximum value of 556.5 mm reported by the Xujiahui station, and a minimum value of 459.6 mm, 96.9 mm less than the former, by the Jinshan station. There is a distinct "rain island" in the central urban area. The precipitation is the highest in the central urban area and goes on a decline when moving farther into the surrounding suburban areas.

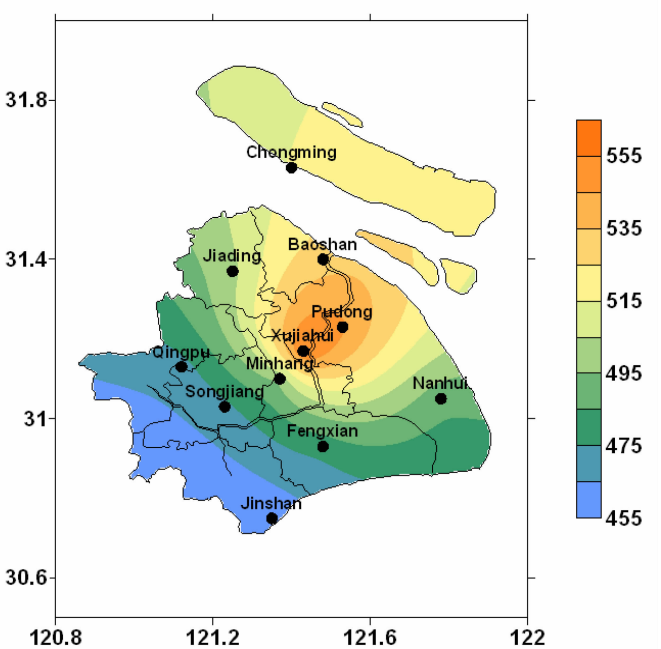

Figure 1. Distribution of mean summer precipitation and the 11 meteorological stations in Shanghai.

For the purpose of this paper, an effective precipitation hour is defined as an hour with no less than 0.1 mm of water falls. Precipitation events are classified by duration, ranging from 1 to 72 hours. A precipitation event must not have a one-hour or longer pause, otherwise it is counted as two separate precipitation events.

It is necessary to standardize precipitation events of different durations and intensities in order to compare them[7]:

$$D_a(h)=\left(\frac{R_a(h)}{\frac{1}{24}\sum_{i=1}^{24}R_a(i)}-1\right)$$

where $R_a(h)$ represents the total precipitation of a type of events at the hour h, i the standard time of the studied area, and $D_a(h)$ the standardized precipitation.

3 BASIC CHARACTERISTICS OF HOURLY PRECIPITATION

Figure 2a illustrates diurnal variations of the mean hourly amount and frequency of summer precipitation in Shanghai. The figure shows markedly varying precipitation amounts and frequencies at different times of the day. Firstly, the maximum in the diurnal cycle of precipitation occurs between the afternoon and the evening (15:00–18:00), which accounts for 22.4% of the total precipitation. The early morning (5:00–8:00) is also a period with relatively high precipitation, which accounts for 16.2% of the total precipitation. On average, precipitation is the lowest at midnight (23:00 –2:00), which is approximately 180 mm, accounting for 12.8% of the total. The precipitation frequency peaks twice, in the

afternoon and the early morning, with the peak value of the former higher than that of the latter. From the diurnal variation trend of precipitation, it can be inferred that summer precipitation in Shanghai is dominated by light rain in the early morning and short-duration heavy rain in the afternoon.

There are also significant interdecadal variations in the afternoon peak of hourly precipitation in Shanghai. According to the historical precipitation data from 1981 to 2015, the characteristics of precipitation afternoon peak are the most significant in the mid-1980s, the late 1990s to the early 21st century and the 2010s. Affected by climate change and urbanization around the 2010s, the peak characteristics of afternoon precipitation (both of amount and frequency) prolonged significantly which may be related to the increase of urban heat capacity (Fig. 2b and Fig. 2c).

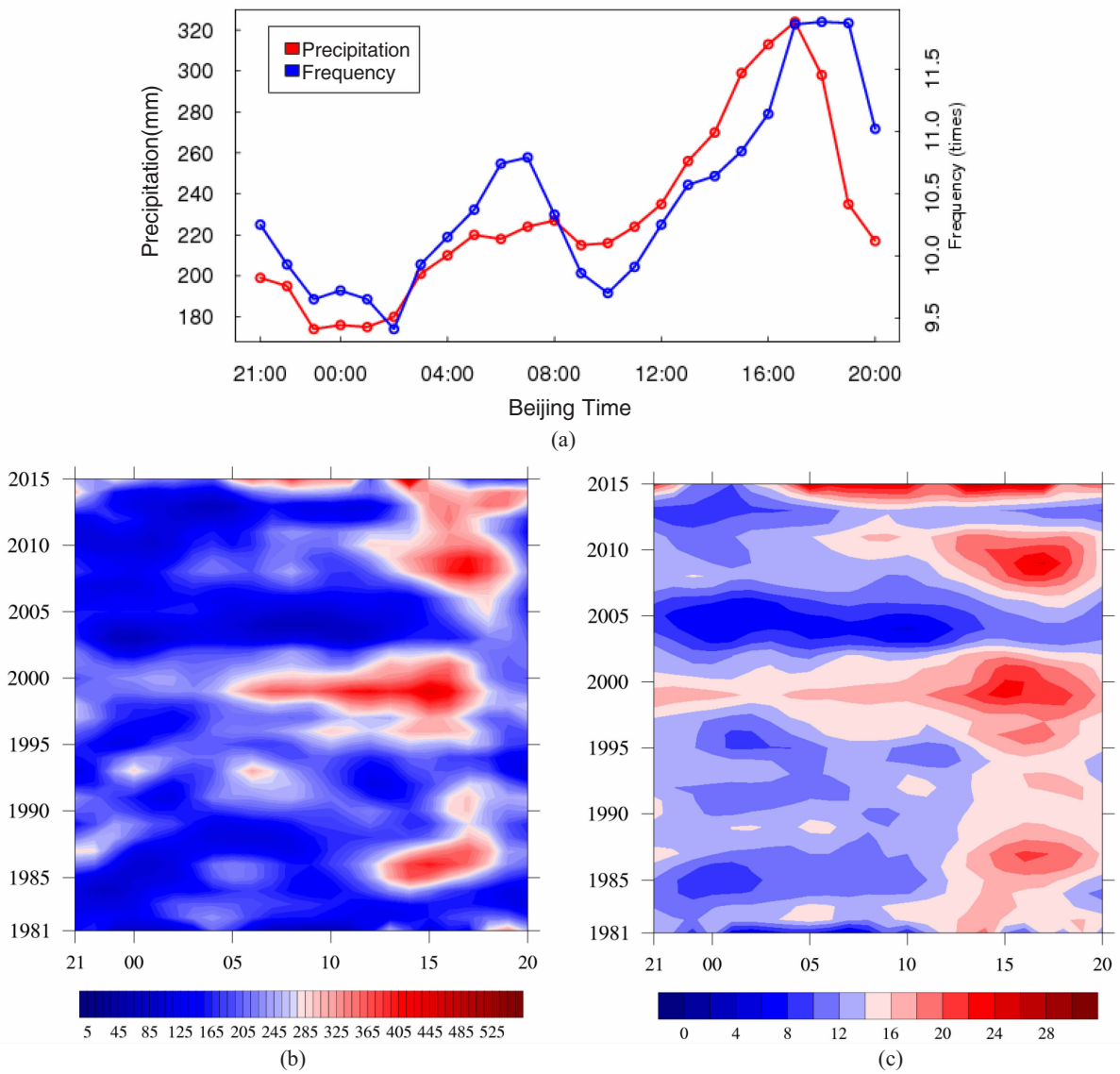

Figure 2. The diurnal cycle of amount and frequency in average (a) and in each year (b, c) from 1981-2015.

To further verify the above inference, according to the hourly precipitation amount, the events are classified into four categories: light to moderate rain (0.1–0.9 mm/h), moderate to heavy rain (1–2.4 mm/h), heavy rain to rainstorm (2.5–9.9 mm/h) and heavy rainstorm (>10 mm/h). Fig. 3 presents the diurnal variation patterns of precipitation of different intensities in Shanghai from 1981–2015. The charts show notable differences among the diurnal variations of precipitation of different intensities. Light to moderate rains mostly fall at the first half of the night (20:00–01:00), with precipitation accounting for 7.95% of the total (Fig. 3a). Moderate to heavy rains are relatively well-distributed except for a trough in the afternoon. The maximum value occurs around midnight. Precipitation of this intensity accounts for 22.5% of the total (Fig. 3b). Rainstorm peaks in the morning and reaches the highest at around 8:00, and the trough period lasts from the evening to the early morning. Rainstorm accounts for 37.3% of the total precipitation (Fig. 3c). Heavy rainstorm mostly falls in

the afternoon. This may be related to the strong solar radiation during this time of the day, which can lead to convection and thus trigger a rainstorm. This type of precipitation contributes to up to 60.6% of the total (Fig. 3d).

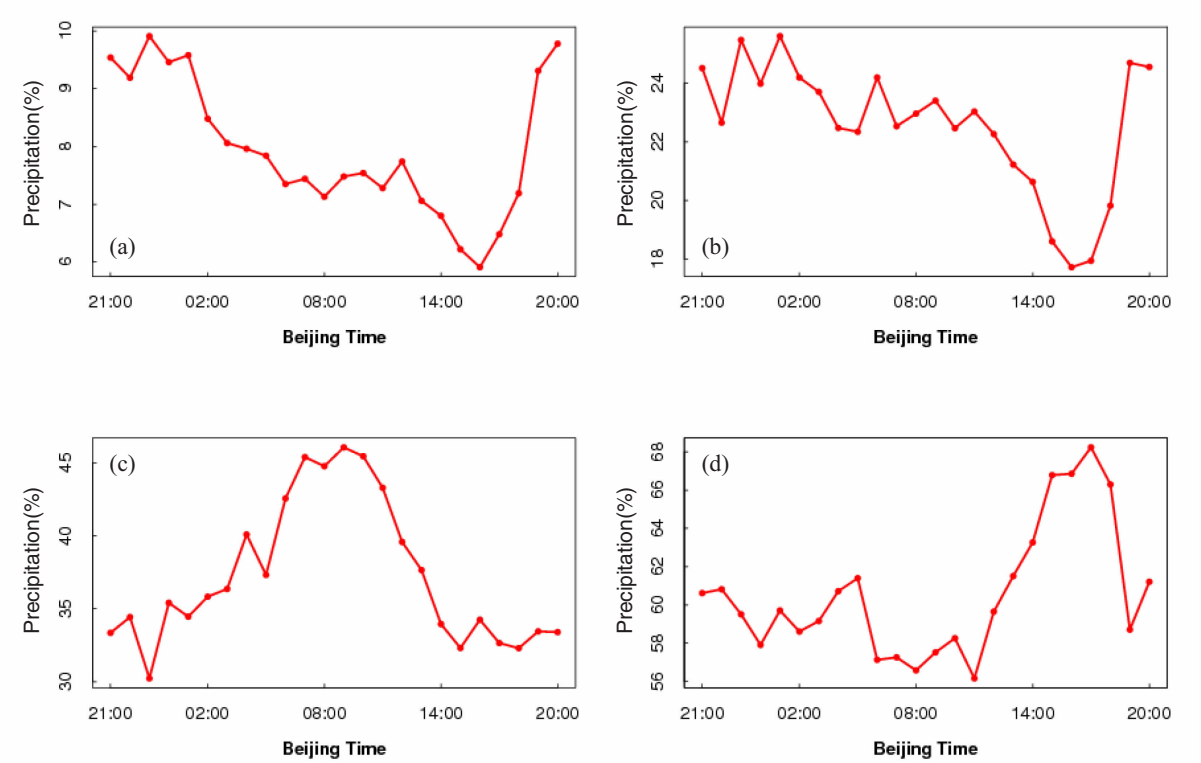

Figure 3. Curves for diurnal variations of precipitation of (a) 0.1–1 mm/h, (b) 1–2.5 mm/h, (c) 2.5–10 mm/h and (d) >10 mm/h.

4 CHARARTERISTICS OF SHORT AND LONG DURATIONS

Yu et al.[7] pointed out that, in eastern China, the diurnal cycle of long-duration precipitation (>6 hours) exhibits an early morning maximum and that of short-duration precipitation (1–3 hours) an afternoon to evening maximum. As for the summer in Shanghai (see Fig. 4), short-duration precipitation events lasting for 2–3 hours are the mainstream among precipitation events of various durations. Cumulative precipitation of this duration can reach approx. 570 mm throughout the summer. Cumulative precipitation of events lasting for 4–5 hours is about 450 mm. During the study period, the cumulative precipitation of each duration decreases with the increase of precipitation duration.

Based on Fig. 4, according to the duration of precipitation events, all precipitation events are classified into four categories: 1–3h, 4–6h, 7–12h and > 13h. The differences of these four types of precipitation events in different times are further analyzed. Fig. 5 demonstrates the standardized curves of precipitation events of different durations in Shanghai. As shown in the figure, the shorter the duration of a precipitation event is, the higher its afternoon maximum and the lower its early morning maximum. The precipitation of 1–3h events peaks at around 16:00 with the maximum value twice the average

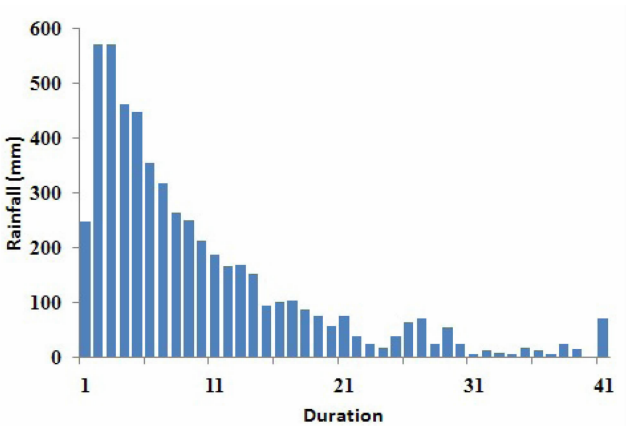

Figure 4. Distribution of cumulative precipitation of different durations ("41" represents the cumulative precipitation of events lasting for more than 40 hours).

precipitation of events of the same duration throughout the day. Maximum precipitation of 4–6h events occurs at around 18:00, 1.5 times the daily average precipitation of the same duration, but with a lower intensity than that of 1–3h duration events. As for long-duration events of 7–12h and >13h, the precipitation reaches its greatest in the early morning. Moreover, the longer the duration is, the higher the early morning maximum and the lower the afternoon maximum.

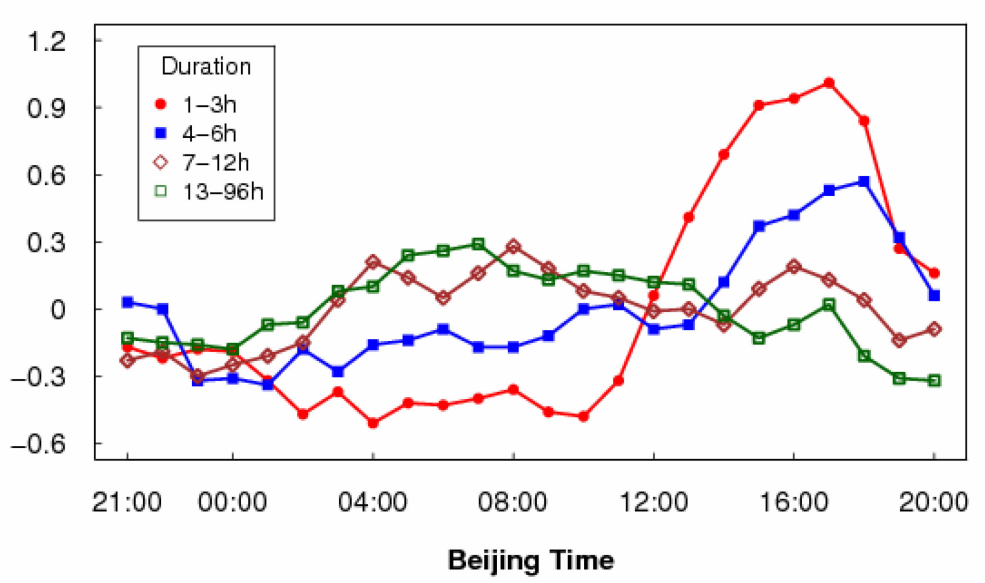

Figure 5. Standardized curves of precipitation events in different duration categories.

5 SPATIAL DISTRIBUTION OF SHORT AND LONG DURATIONS

To study the spatial distribution of summer precipitation events in Shanghai, we worked out the percentage share of precipitation of each duration in the total precipitation and the time of the day when maximum precipitation occurs using the data provided by the 11 meteorological stations from 1981 to 2015 (see Fig. 6).

Generally, the proportion of short- and long-duration precipitation does not show much difference among different parts of the city. The city center and coastal areas are dominated by short-duration precipitation (see Fig. 6a). Short-duration events observed at the Xujiahui and Pudong stations each account for over 50% of the total. The inland area and the Chongming Island in the north are dominated by long-duration precipitation (see Fig. 6b), with the highest proportion being 54.5% , observed at the Qingpu station. In terms of the time when precipitation reaches a peak, short-duration precipitation has an afternoon to evening maximum, whereas long-duration precipitation roughly shows an early morning maximum, which, as observed at the stations, occurs slightly later in the west than it does in the east.

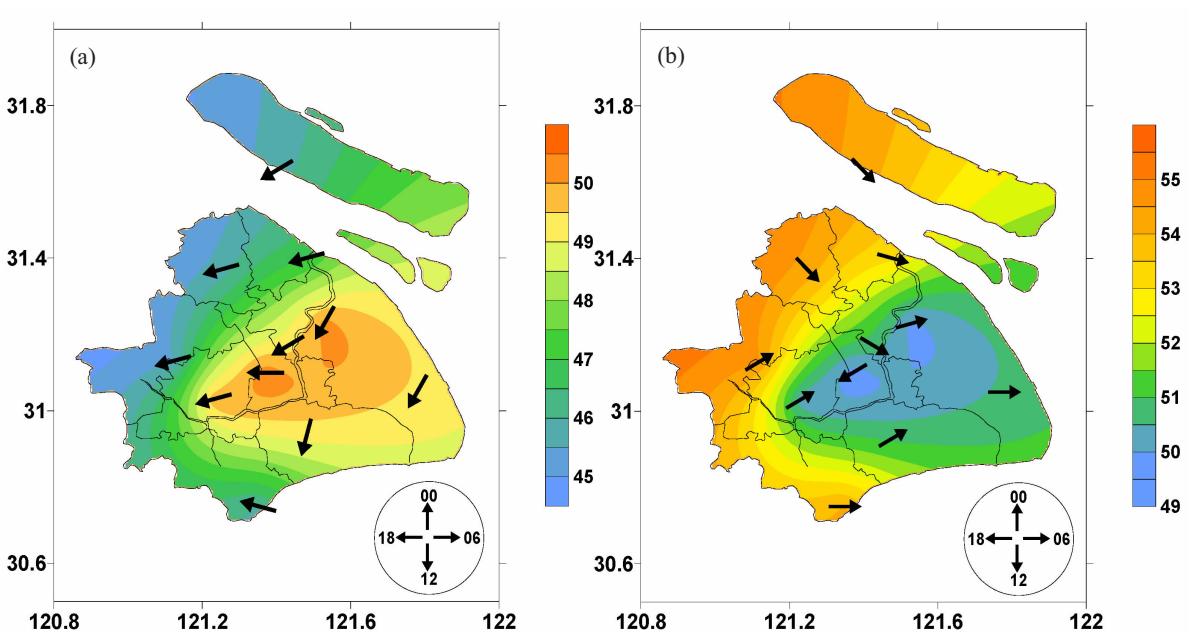

Figure 6. Percentage share of precipitation of different durations in total summer precipitation and the time of the day when maximum precipitation occurs (a: 1–6h, and b: 7–12h).

Here we divide the 11 meteorological stations of Shanghai into three types based on the percentage share of precipitation of different durations in the total precipitation. Chongming, Jiading, Qingpu and Songjiang are type I stations that represent the western area. Fengxian and Jinshan are classified as type II stations to represent the southern coastal area. Type III stations include Baoshan, Minhang, Xujiahui, Pudong and Nanhui, representing the central urban and eastern coastal area. Analyses are performed on the diurnal variations of precipitation of different durations for each of the three types of stations (see Fig. 7). As for 1–6h short-duration events, an afternoon maximum is observed at all the three types of stations and higher maximum values are reported from type I and III stations. 7–12h long-duration events as well as 13h and 13h+ super-long-duration events show an early morning precipitation maximum, which is the most apparent at type II stations. The precipitation proportion of super long events is slightly larger in the inland area (type I) than in the central urban and eastern coastal area (type III).

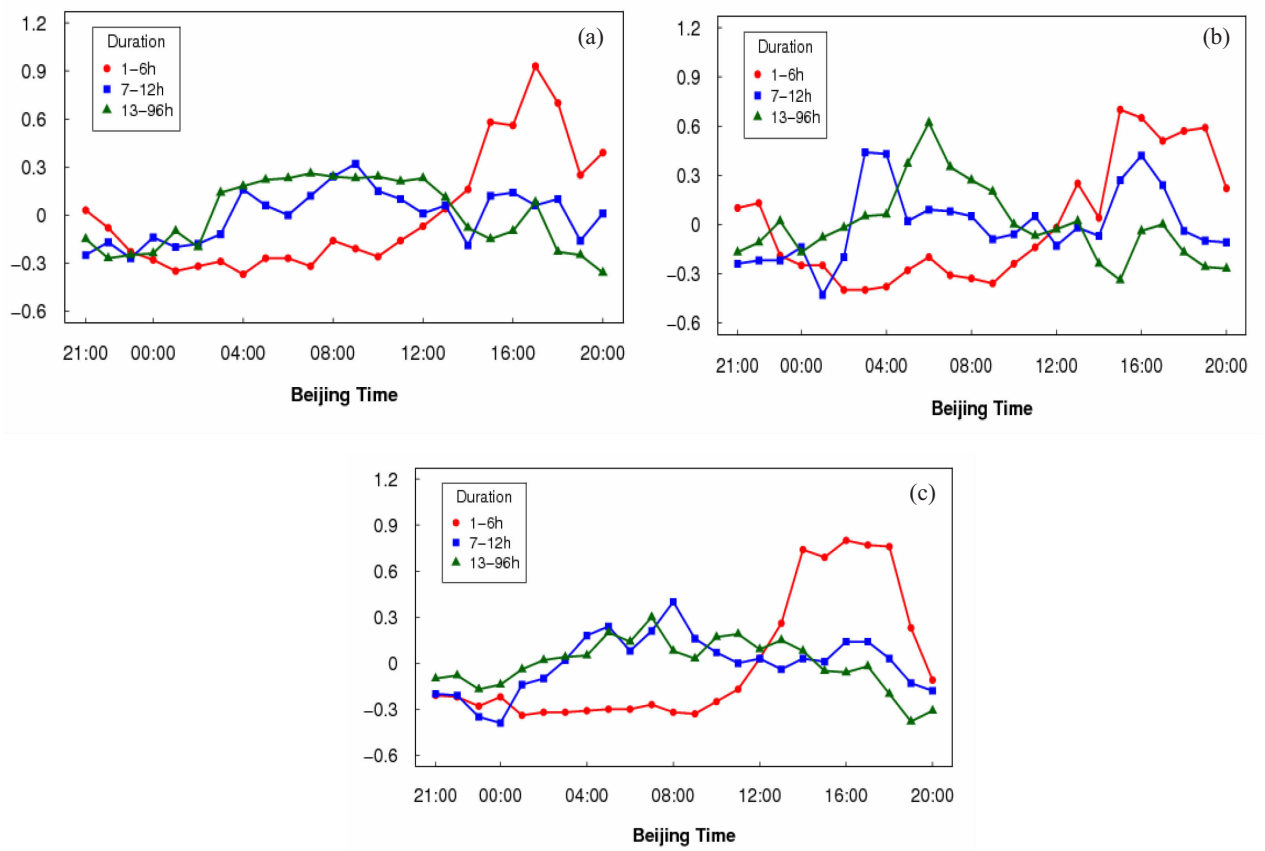

Figure 7. Standardized precipitation curves of precipitation events of different durations as observed at three types of stations (a: type I, b: type II, and c: type III).

6 CONCLUSIONS AND DISCUSSION

This paper investigates the diurnal variations of summer precipitation in Shanghai by using the city's hourly precipitation data over a 35-year period from 1981–2015.

Generally, both the precipitation amount and frequency in Shanghai show an afternoon maximum, but the frequency also reaches a significant peak in the early morning. From the perspective of precipitation intensity, small to moderate rains often fall from midnight to the early morning. As the intensity increases, the precipitation peak occurs at an increasingly late time of the day. For example, violent rains reach a precipitation peak at around 14:00. As far as duration is concerned, short-duration events usually reach a precipitation peak in the afternoon and in the evening, while long-duration precipitation mostly peaks in the early morning. Spatial variations take on three main patterns. The precipitation in the eastern coastal and central urban area reaches a peak in the afternoon. The precipitation in the southern coast peaks twice, at night and in the afternoon. Super long precipitation accounts for a larger proportion in the western area than in the other two areas.

Yu et al.'s works [7, 8] revealed that short-duration precipitation events occurring in the afternoon and around the evening are closely related to solar radiation heating. Due to the diurnal variations of solar radiation heating, the lower atmosphere tends to reach an unstable state in the afternoon and the evening, bringing out zonal moist

convection that results in short-term precipitation. However, the precipitation peak in the early morning has much more complicated formation mechanisms. Some scholars suggest that precipitation peaks occurring at night result from stratiform precipitation, which is enhanced by the instability caused by radiative cooling near the cloud top at nighttime [17]. Others believe that the accumulation of water vapor in the lower layer of the atmosphere promotes the nocturnal convection significantly [18].

On the other hand, there are great spatial discrepancies in the precipitation patterns of Shanghai despite its relatively small geographical span. Further studies are required to discuss whether this precipitation diversity results from the special geographical location of Shanghai, a city backed by the continent and surrounded by water on three sides. One factor to consider, for example, would be the increased urban surface roughness due to intense urbanization in the central urban area. The focus should be put on whether this factor leads to increased regional convergence [19, 20], higher sensible heat flux, and decreased instability of the boundary layer [21], and whether these issues add to the impact of urbanization on large-scale environments to cause the diurnal variations of precipitation in Shanghai.

REFERENCES:

[1] WALLACE J. Diurnal variations in precipitation and thunderstorm frequency over the conterminous United States [J]. Mon Wea Rev, 1975, 103(5): 406-419.

[2] DAI A G, GIORGI F, TRENBERTH K. Observed and model-simulated diurnal cycles of precipitation over the contiguous United States [J]. J Geophys Res, 1999, 104 (D6): 6377-6402.

[3] YANG G Y, SLINGO J. The diurnal cycle in the tropics [J]. Mon Wea Rev, 2001, 129(4): 784-801.

[4] DAI A G. Global Precipitation and thunderstorm frequencies, Part Ⅱ: Diurnal variations [J]. J Clim, 2001, 14(6): 1112-1128.

[5] LIANG X Z, LI L, DAI A G, et al. Regional climate model simulation of summer precipitation diurnal cycle over the United States [J]. Geophys Res Lett, 2004, 31: L24208, doi: 10.1029/2004GL021054.

[6] WANG Y Q, ZHOU L, HAMILTON K. Effect of convective entrainment/detrainment on the simulation of the tropical precipitation diurnal cycle [J]. Mon Wea Rev, 2007, 135(2): 567-585.

[7] YU R C, ZHOU T J, XIONG A Y, et al. Diurnal variations of summer precipitation over contiguous China [J]. Geophys Res Lett, 2007a, 34: L01704, doi: 10.1029/2006GL028129.

[8] YU R C, XU Y P, ZHOU T J, et al. Relation between rainfall duration and diurnal variation in the warm season precipitation over central eastern China [J]. Geophys Res Lett, 2007b, 34: L13703, doi:10.1029/2007GL030315.

[9] ZHOU T, YU R, CHEN H, et al. Summer precipitation frequency, intensity, and diurnal cycle over China: A comparison of satellite data with rain gauge observations [J]. J Clim, 2008, 21(16): 3997-4010.

[10] YUAN W, YU R, CHEN H, et al. Subseasonal characteristics of diurnal variation in summer monsoon rainfall over central eastern China [J]. J Clim, 2010, 23 (24): 6684-6695.

[11] LI J, YU R C, WANG J J. Diurnal variation characteristics of summer precipitation in Beijing[J]. Chin Sci Bull, 2008, 539(7): 829-832.

[12] YIN S Q, GAO G, LI W J, et al. Long-term precipitation change by hourly data in Haihe River Basin during 1961-2004 [J]. Sci China: Earth Sci, 2011, 54 (10): 1576-1585, doi:10.1007/s11430-011-4232-z.

[13] ZHOU H, ZHAO P, ZHOU T J. Diurnal cycle of summer rainfall in Shandong of eastern China [J]. Int J Climatol, 2013, doi:10.1002/joc.3718.

[14] TANG Hong-yu, GU Jian-feng, YU Sheng-bin, et al. Analysis on diurnal variation of precipitation in southwest China [J]. Plateau Meteor, 2011, 30 (2): 376-384 (in Chinese).

[15] DAI Ze-jun, YU Ru-cong, LI Jian, et al. The characteristics of summer precipitation diurnal variations in three reanalysis datasets over China [J]. Meteor Mon, 2011, 37(1): 21-30 (in Chinese).

[16] DAI Ze-jun, YU Ru-cong, CHEN Hao-ming. Characteristics of summer precipitation diurnal variations in Hunan [J]. Plateau Meteor, 2009, 28(6): 1463-1469 (in Chinese).

[17] LIN X, RANDALL D A, FOWLER L D. Diurnal variability of the hydrologic cycle and radiative fluxes: Comparisons between observations and a GCM [J]. J Clim, 2000, 13(23): 4159-4179.

[18] NESBITT S W, ZIPSER E J. The diurnal cycle of rainfall and convective intensity according to three years of TRMM measurements [J]. J Clim, 2003, 16 (10): 1456-1475.

[19] CHANGNON S A, SEMONIN R G, AUER A H, et al. METROMEX: A review and summary [J]. Meteor Monogr, 1981, 18(1): 181pp.

[20] BORNSTEIN R, LIN Q. Urban heat islands and summertime convective thunderstorms in Atlanta: Three case studies [J]. Atmos Environ, 2000, 34(3): 507-516.

[21] SHEPHERD J M, PIERCE H, NEGRI A J. Rainfall modification by major urban areas: Observations from space borne rain radar on the TRMM satellite [J]. J Appl Meteor, 2002, 41(7): 689-701.

Citation: HOU Yi-ling and CHEN Bao-de. Diurnal variations of summer precipitation in Shanghai [J]. J Trop Meteor, 2019, 25(3): 414-420.