The Statistical Relationship of Lightning Activity and Short-Duration Rainfall Events over Guangzhou, China, in 2017

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ABSTRACT: The Earth Networks Total Lightning Network (ENTLN) lightning observation and rainfall data from 270 automatic weather stations (AWS) over Guangzhou in 2017 are examined. The high spatiotemporal resolution data are used to analyze the relationship between lightning activity and precipitation in 14758 short-duration rainfall (SDR) events. About 43% of the SDR events are reported to be accompanied by lightning activity (SDRWL). The rainfall intensity of SDRWL is significantly higher than that of SDR events with no lightning (SDRNL). Lightning activity is more likely to occur in SDR events with higher rainfall rates. A power-law relationship is found between lightning flash rate and rainfall rate, with a max correlation coefficient of 0.44. In about 55% of SDRWL, lightning flashes occur later than precipitation, and the opposite is found in about 35% of SDRWL. When lightning is delayed for 5–10 min, the lagged correlation coefficient between lightning and precipitation is the largest. The results also show that the lightning flash rate peak mostly occurs from −10 to 20 min after the rainfall rate peak, and this time lag is common in SDRWL with all intensities. The starting time of lightning is related to the rainfall intensity. In heavy SDRWL, lightning activity usually occurs from −10 to 20 min after the beginning of precipitation, while in weak SDRWL, the above time window expands to ±1 h. These results indicate that the quantity and time relationship between lightning and precipitation are more solid in heavy SDR events.

KEYWORDS: Lightning; Rainfall; Statistics

1. Introduction

Along with complicated cloud microphysics and dynamic processes, lightning and precipitation often occur together in thunderstorm clouds. Both heavy rainfall and lightning have significant impacts on daily life, with a close relationship between them. Noninductive charging has been found as the primary charging mechanism in thunderstorms in numerous field campaigns and laboratory research (Latham et al. 2007; Mansell et al. 2005; Saunders 1993; Saunders and Peck 1998; Saunders et al. 1991; Takahashi 1978; Takahashi and Miyawaki 2002). The interaction between supercooled water, ice crystal, graupel, and other liquid or solid water droplets contributes significantly to the noninductive charging, which is also of great importance in the heavy rainfall process. The ice-phase microphysical processes can produce a mass of positive and negative charges that are then transported by intense updrafts in thunderstorms, eventually leading to the generation of lightning flashes. Lightning intensity depends on the intensity of the electric field in clouds that is closely associated with the dynamical and microphysical processes in thunderstorms. Meanwhile, these dynamical and microphysical processes are directly associated with the generation of thunderstorm clouds and precipitation particles, which finally determines the occurrence of heavy rainfall and severe weathers (Bergeron 1935; Field and Heymsfield 2015; Gaskell 1981; Gilmore et al. 2004; Jayaratne and Saunders 1985; Lang et al. 2004; Pereyra et al. 2000; Qie et al. 2021; Reynolds et al. 1957; Saunders 1993; Takahashi 1978).

The relationship between lightning and rainfall has long been recognized. Even in ancient times, this relationship was observed and recorded by ancient folks. As described in the old Chinese proverbs: "Hearing the thunder and seeing the crossing lightning in the sky, then the hail follows as big as bowls." "Vertical lightning heralds the weak precipitation, while horizontal lightning heralds the intense precipitation." With the development of detection techniques, the study on this relationship has been carried on worldwide. Petersen and Rutledge (1998) calculated the ratio of the mean rainfall to lightning flash counts (i.e., the rain yields) over multiple regions. Although this ratio varies worldwide, it remains stable in the local area. Price and Federmesser (2006) examined lightning and rainfall in winter thunderstorms over the eastern Mediterranean Sea with 6-yr (1998–2003) Tropical Rainfall Measuring Mission (TRMM) observations. A strong correlation between total flash rate and rainfall rate has been found, and the monthly and seasonal correlation coefficients between rainfall and lightning vary between 0.81 and 0.98. Lal and Pawar (2009) analyzed 10-yr TRMM lightning and rainfall observation over central India. A positive correlation is found between rainfall and lightning during the pre-monsoon period. While during the monsoon period, the narrower

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updraft, the smaller size of storm-scale convection, and lower aerosol concentration led to a poorer correlation than in premonsoon seasons (Williams and Stanfill 2002; Williams et al. 2002). A similar decrease has also been found in South China (Luo et al. 2013). Xia et al. (2015) examined cloud-to-ground (CG) lightning climatology and its relationship to rainfall over central and eastern China, using data from 6-yr CG observation and TRMM data covering 2008–13. The results showed that lower-flash-density days occur over mountainous regions due to the development of short-lived afternoon storms, while higher-flash-density days appear typically associated with nocturnal thunderstorms. Xu et al. (2013) examined the lightning activity and convective rainfall in the southern United States with 13-yr (1998–2010) TRMM data. Significant correlations are found between storm-scale lightning parameters and convective rainfall for systems. Storm-scale convective rainfall or heavy-precipitation area has the best correlation (coefficient r = 0.75–0.85) with the lightning-flash area. Statistics further show that active lightning and intense precipitation are not well collocated. These studies have shown that, although the correlation may vary significantly in different regions and seasons, a positive correlation between lightning and rainfall is reported across the world. The spatial distribution of lightning and precipitation is relatively consistent, and there is a proportional relationship in quantity.

Besides the statistics studies mentioned above, other researchers pay more attention to the lightning activity and precipitation in individual thunderstorms. These studies show that, in some cases, lightning activity may be a good indicator for the following convective rainfall and severe weather (Chronis et al. 2015; Farnell et al. 2017; Koutroulis et al. 2012; Price and Federmesser 2006; Schultz et al. 2011; Soula et al. 1998; Tapia et al. 1998; Wu et al. 2018). Compared with the large-scale statistics, these studies focus on the relationship between cloud structure and lightning position, the spatial distribution of rainfall and lightning density, as well as temporal relationship of lightning and precipitation (Feng et al. 2007; Gungle and Krider 2006; Seity et al. 2001; Wapler 2017). However, most of the previous studies focused on the lightning activity and rainfall of only several thunderstorm cases or over a particular period. It is known that the characteristics of lightning and precipitation can vary significantly in thunderstorms with different types and intensities. More observation data are needed for better understanding this relationship.

Based on satellite, radar, and weather station observation, short-duration rainfall (SDR) events are usually defined as rainfall events lasting for several hours in duration on a relatively small scale (Hwang et al. 2020; Prajapati et al. 2022; Wu et al. 2017). SDR events have been reported to induce flash floods, urban waterlogging, landslides, and many other losses (Brooks and Stensrud 2000; Fowler et al. 2021). Previous studies have conducted statistical analyses of SDR events over China by examining high spatiotemporal-resolution station rainfall observation, which improves the understanding of heavy rainfall (Yuan et al. 2014; Li et al. 2017). Recent studies showed that both short-duration (subdaily) and long-duration (>1 day) rainfall extremes are intensifying under global warming, while in some regions, the increases of SDR extreme are stronger than those of mean precipitation (Fowler et al. 2021; Zhang et al. 2017). Cities are particularly vulnerable to intensifying SDR events. For example, the drainage, tunnels, and subway systems built with a capacity based on the historically lower rainfall intensities will face more risks in future warming climate. This vulnerability necessitates further research on the SDR events, especially in metropolitan regions.

Guangdong is one of the most vulnerable regions to both intense lightning activity and precipitation in China (Q. Zhang et al. 2011; W. Zhang et al. 2011). As the capital of Guangdong, Guangzhou has a developed economy and a large population, the frequent intense lightning activity and precipitation often bring heavy property losses and casualties. The relationship between rainfall and lightning activity during SDR events has been investigated over other metropolitan regions in China. For example, Wu et al. (2017) investigated the relationship between lightning and rainfall during SDR events over Beijing, using 2-yr (2006–07) automatic station rainfall data and SAFIR-3000 lightning observation. The results showed that the lightning activity in more than half of the 2925 SDR events precedes precipitation. And the correlation coefficients between lightning flashes and rainfall are higher in heavy events than in weak ones. Yet, similar studies have seldomly been conducted in Guangzhou. With the intensifying rainfall extremes under global warming (Fowler et al. 2021; Zhang et al. 2017) as well as the increasing lightning activity over metropolitan regions (Kar et al. 2009; Orville and Huffines 2001; Wang et al. 2011), the studies on both rainfall and lightning activity during SDR events over Guangzhou are of great significance. In this study, two main concerns will be addressed: (i) What are the characteristics of lightning and precipitation in SDR events from high-resolution observations over Guangzhou? (ii) What is the relationship between lightning and rainfall in SDR events? The results could provide useful references for related statistical understanding and support future research on establishing possible early warning approaches for heavy rainfall in SDR events over this region (Wu et al. 2018). The next section describes the data and methods used in this study. Section 3 documents the statistical analysis of lightning activity and rainfall in SDR events, including the spatial–temporal distribution and quantitative and time-lagged relationship. A summary and conclusions are given in the final section.

2. Data and methods

a. *Data, quality control, and preprocessing*

1) Lightning observation data

Lightning data used in this study are derived from the Earth Networks Total Lightning Network (ENTLN) lightning location system observation of 2017 in Guangdong, China. This system was deployed with 10 substations in 2013 and 6 added in 2015 (Fig. 1a). A wide-band (1 Hz–12 MHz) detection technique has been used in ENTLN, which can provide observations for both intracloud lightning (IC) and CG

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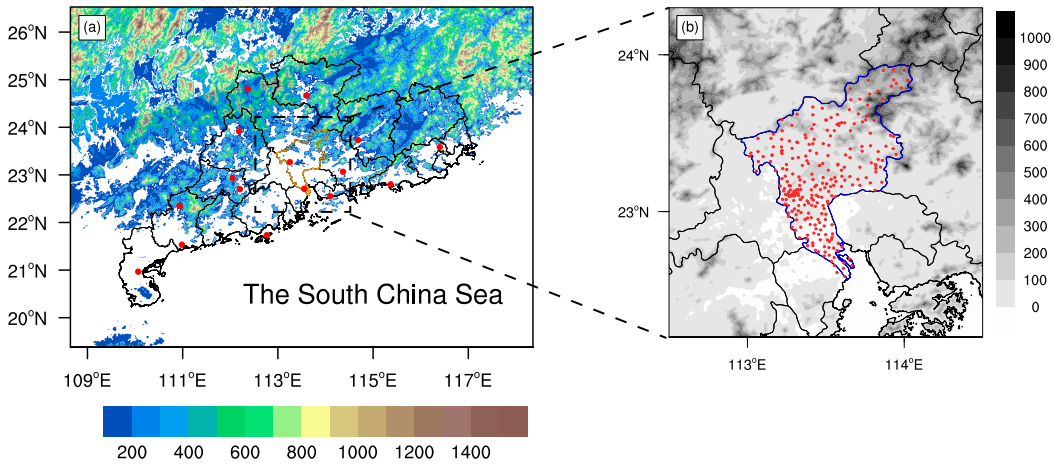

FIG. 1. (a) Locations of the 16 ENTLN substations (red dots), superimposed with topography (shading; m). Black and orange lines denote the borders (and coastlines) of Guangdong Province and Guangzhou city. (b) Locations of the 270 automatic weather stations in Guangzhou (red dots), superimposed with topography (shading; m).

flashes. When a lightning flash is detected, the waveform of this flash is recorded and then reported to a central server. All metadata are processed here to produce detailed lightning information, including flash type (i.e., IC or CG), polarity, multiplicity, occurrence time, position, height, and peak current. Up to now, there has been no published performance evaluation about Guangdong ENTLN. In 2015, a preliminary assessment of ENTLN was carried by Guangdong Meteorological Service. It is reported that the detection efficiency of ENTLN is about 77% (76%) for total flash (strokes), the mean location error is about 685 m, and the mean peak current is about 39% lower than the ground truth, but still highly linear correlated with the ground truth.

In this study, further quality control is carried for the reliability of the statistical analysis. The ENTLN observation data are processed as follows: First, the occurrence position of each flash is determined by the position of the first pulse, and then the lightning flashes outside the study region (Fig. 1b) are excluded. Second, the temporal continuity and peak current of lightning flashes are checked by eliminating flashes with the pulse time intervals of more than 1 s (Wu et al. 2016), and positive CG whose mean peak currents of all pulses are smaller than 10 kA. This removal has been recommended for certain types of lightning detectors, e.g., Cummins et al. (1998), Taszarek et al. (2015), Wu et al. (2016). Although not required with ENTLN data, we deleted them in an abundance of caution.

2) RAINFALL OBSERVATION DATA

The rainfall data used in this study are derived from the automatic weather stations (AWS) observation of 2017 in Guangzhou, China (270 stations, Fig. 1b), with a 5-min interval. The rainfall data are first quality-controlled and then processed to identify SDR events. The quality control and SDR recognition are carried as follows:

(i) The temporal continuity and extreme value of the 5-min interval rainfall series are examined. Records with 5-min rainfall exceeding 40 mm are regarded as false values and eliminated. Only rainfall series with no missing or false values are used in the following SDR identification.

(ii) When the 5-min cumulated rainfall of a particular AWS is greater than 0.1 mm, and the subsequent 1-h rainfall exceeds 5 mm, this moment is defined as the beginning time (T_{start}) of an SDR event on this AWS. An SDR event is considered to end when the subsequent 1-h accumulated rainfall is less than 5 mm. This moment is defined as the end time of an SDR event (T_{end}). Thus, the duration of an SDR event is defined as $T_{\mathrm{sus}} = T_{\mathrm{end}} - T_{\mathrm{start}}$. With T_{start} and T_{end}, an SDR event at an individual AWS can be clearly defined.

(iii) After the SDR events are identified, they are classified into different grades according to their rainfall intensity. In the previous studies, usually, the accumulated rainfall during the SDR event is used to indicate the SDR intensity (Polemio and Lonigro 2015; Wu et al. 2017; Yu et al. 2007). While in this study, different statistic characteristics are found when the mean rainfall rate during SDR is considered, compared to the accumulated rainfall (Tables 1, 2 and Fig. 6). Therefore, SDR events are graded in two different ways: mean rainfall rate (5–10, 10–20, 20–30, 30–40, 40–50, and ≥50 mm h^{-1}) and accumulated rainfall (5–10, 10–20, 20–30, 30–40, 40–50, and ≥50 mm) for better understanding of the relationship between rainfall and lightning in SDR events with different intensity. To keep the sample sizes produced

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TABLE 1. Number and mean duration of SDR events with different accumulated rainfall.

	Grade1 [5–10 mm)	Grade2 [10–20 mm)	Grade3 [20–30 mm)	Grade4 [30–40 mm)	Grade5 [40–50 mm)	Grade6 (≥50 mm)	Sum
No.	5188	4922	1976	999	519	1154	14 758
Percentage (%)	35.1	33.4	13.4	6.8	3.5	7.8	100
Cumulative (%)	35.1	68.5	81.9	88.7	92.2	100	—
Mean duration (min)	38.1	54.4	71.4	90.7	105.3	187.9	65.6

by the above two grading methods as close as possible, SDR events with accumulated rainfall less than 5 mm and duration less than 1 h are excluded.

b. Methods

Two problems are needed to be solved before examining the relationship between lightning and rainfall: (i) the lightning and rainfall observation data must be appropriately matched because the lightning surveillance is over the whole study region. In contrast, rainfall observation is carried on fixed stations; and (ii) the lightning and rainfall data are derived from two independent systems. At present, there is no assessment of the joint-observation ability of these two systems. The observation errors of two independent systems may negatively affect the matching of lightning and rainfall. Thus, measures need to be taken to reduce these potential effects.

For the former problem, two kinds of solutions have been proposed in the previous studies. One is to track the movement of thunderstorms and examine the lightning activity and precipitation inside thunderstorms (Gungle and Krider 2006; Holle and Bennett 1997; Piepgrass et al. 1982). The other one is to find the best searching radius. Namely, the lightning flashes in the circular area with this searching radius around the AWS are regarded to be produced by the same weather system when the rainfall is recorded. In this study, the searching radius is adopted. Because the data used in this study are over an entire year and searching radius can provide fast matching for the lightning and rainfall data in all kinds of weather systems. Moreover, the spatial distribution of lightning and rainfall can vary significantly in different thunderstorms, and a fixed searching radius can reduce the uncertainty of matching. Usually, the searching radius is set from a few to tens of kilometers for the sparsely distributed stations. In comparison, the average distance between two nearest AWSs in this study is about 4.7 km (Fig. 1b). A large searching radius will lead to the overlap of the searching area around the AWSs. Lightning flashes that occurred in the overlapped areas will then be matched with irrelated SDRs, which may bring misunderstanding to the relationship between lightning and rainfall. Thus, we used a 5-km searching radius to match the rainfall and lightning flashes around the AWS, which can reduce overlapped searching area and provide enough lightning flashes for matching with SDR events.

For the latter problem, it is hard to evaluate the lightning detection efficiency in an SDR event, so the matching is carried with rainfall data strictly examined. Namely, the rainfall series can be considered reliable after quality control with no missing or false value, and all of the SDR events are identified within these series. Only the lightning flashes that occurred during the period of the trusted rainfall series are checked to determine whether it is within the SDR duration or not. Other lightning flashes are excluded from the statistics, for there is no reliable rainfall observation at the same time. With these measures, we can ensure the validity of the data used in this study.

In the previous studies, weather systems are usually classified by seasons (cold or warm, monsoon or non-monsoon) or types (convective or non-convective) to examine the characteristics of lightning and rainfall in different weather systems. In this study, observation data of one year are analyzed, and exploring the long-term relationship between lightning and rainfall is one of the major motivations of this study. Thus, no other classification or elimination was performed on the data except the necessary quality control and processing mentioned above.

3. Results

a. Spatial distribution of rainfall and lightning flash density

In 2017, the total annual rainfall of SDR events in Guangzhou exceeded 1500 mm and was unevenly distributed. A large annual rainfall zone with a nearly northwest–southeast shape of more than 2100 mm can be found in the city center (Fig. 2a). According to the topographic distribution in Guangzhou (Fig. 1b, shaded), the annual rainfall centers are mostly located near the mountainous or hilly terrain. Different from the annual rainfall (Fig. 2a), SDR events are more evenly

TABLE 2. Number and mean duration of SDR events with different rainfall rates.

	Rate1 [5–10 mm h^{-1})	Rate2 [10–20 mm h^{-1})	Rate3 [20–30 mm h^{-1})	Rate4 [30–40 mm h^{-1})	Rate5 [40–50 mm h^{-1})	Rate6 (≥50 mm h^{-1})	Sum
No.	3314	4178	3144	2038	1078	996	14 748
Percentage (%)	22.3	28.2	21.2	13.8	7.4	7.1	100
Cumulative (%)	22.3	50.5	71.7	85.5	92.9	100	—
Mean duration (min)	79.9	82.2	61.3	42.0	39.5	38.9	65.6

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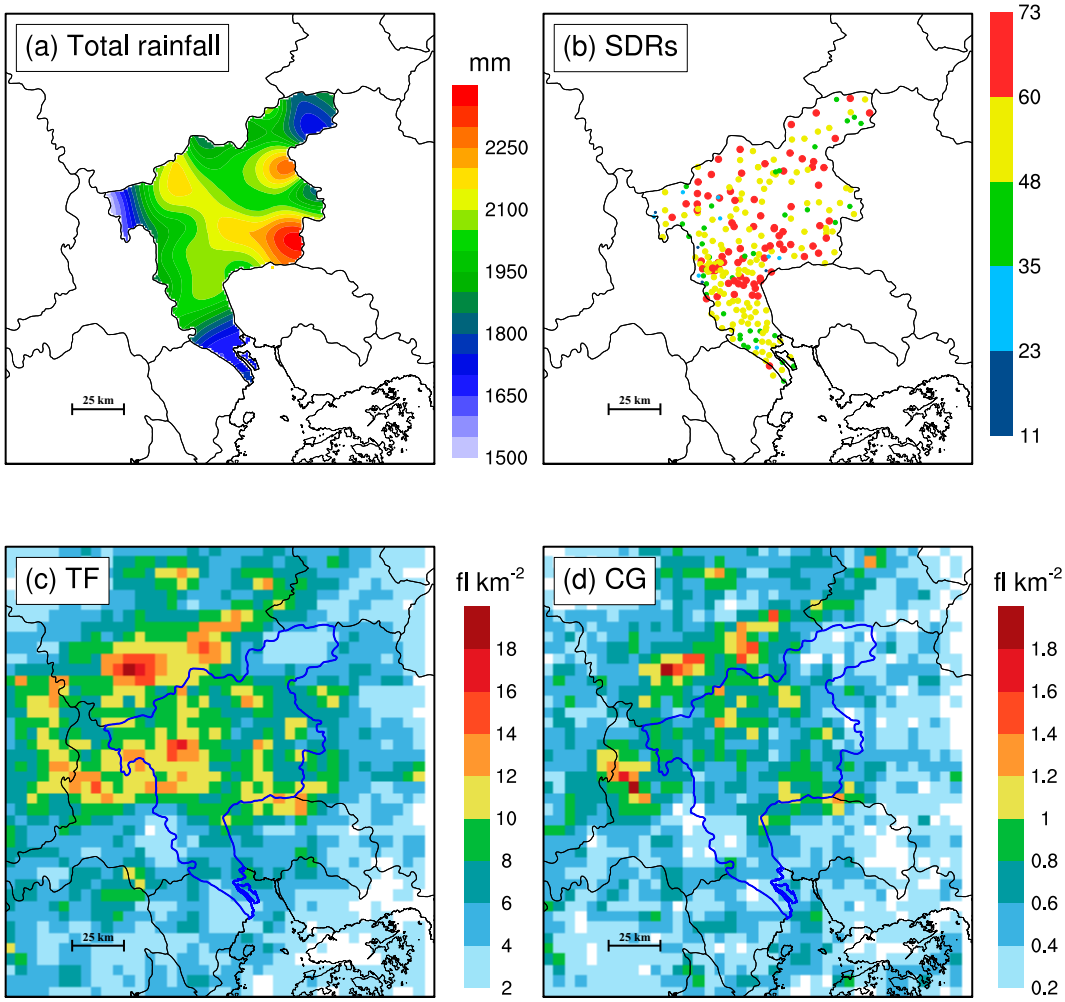

FIG. 2. (a) Annual SDR rainfall, (b) SDR frequency, (c) total flash (TF) density, and (d) cloud-to-ground (CG) density over Guangzhou, 2017.

distributed over the study region (Fig. 2b). Most of the AWSs recorded more than 48 SDR events, with an average of 54, and 92 AWSs reported more than 60 SDR events.

The spatial distribution of annual mean total lightning flash density (Fig. 2c) shows that the mean total flash density in Guangzhou is about 10 flashes km^{-2} yr^{-1} with the maximum exceeding 18 flashes km^{-2} yr^{-1} (Fig. 2c). Large values are mainly located in the northwest foothills and the west center of the city (Fig. 1b), indicating the favorable conditions for the development of thunderstorms over these regions. Annual rainfall and total lightning flash density share a similar spatial distribution. The high total density lies in the area where the annual rainfall exceeds 1950 mm. But the large values of flash density and rainfall distribute separately. High annual rainfall occurs in the east of the city, while high flash density is found in the west (Figs. 2a,c). Annual CG flash density is about one order magnitude less than that of total flash density, and the largest annual CG flash density is about 1.8 km^{-2} yr^{-1}. Of interest is that, although the overall spatial distributions of total flash and CG flash are similar, the detailed distribution can be quite different on a scale of 10 km (Figs. 2c,d). This kind of spatial variation of total flash to CG flash ratio is a clear reflection that thunderstorm systems can continuously bring differences in lightning flash distribution on a small scale in this region and eventually lead to obvious differences in the annual average ratio of total flash to CG flash.

In 2017, 14 758 SDR events were reported by 270 AWSs, with an average of 55. The SDR events are graded into six grades by accumulated rainfall (Table 1), and with the increase of accumulated rainfall, the mean durations of SDR events increase significantly. About 70% of the total SDR events have less than 20 mm rainfall and last about 1 h. SDR events with more than 50 mm rainfall last much longer than SDR events in other grades, with an average duration of 187.9 min. The results vary greatly when SDR events are graded by rainfall rate (Table 2). A total of 14 748 SDR

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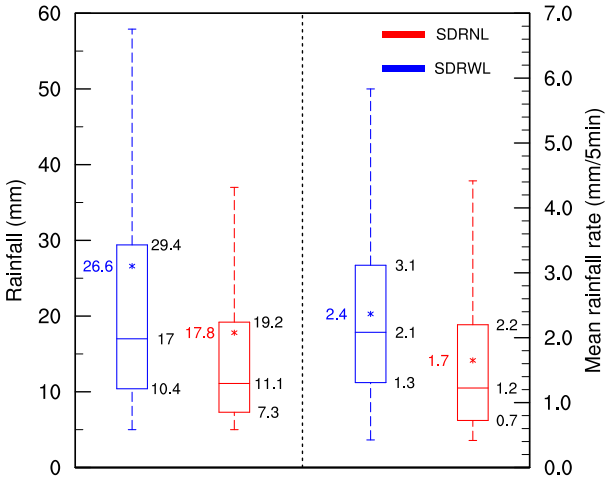

FIG. 3. Boxplots of accumulated rainfall and rainfall rate in SDR events with lightning (SDRWL) and SDR events with no lightning (SDRNL).

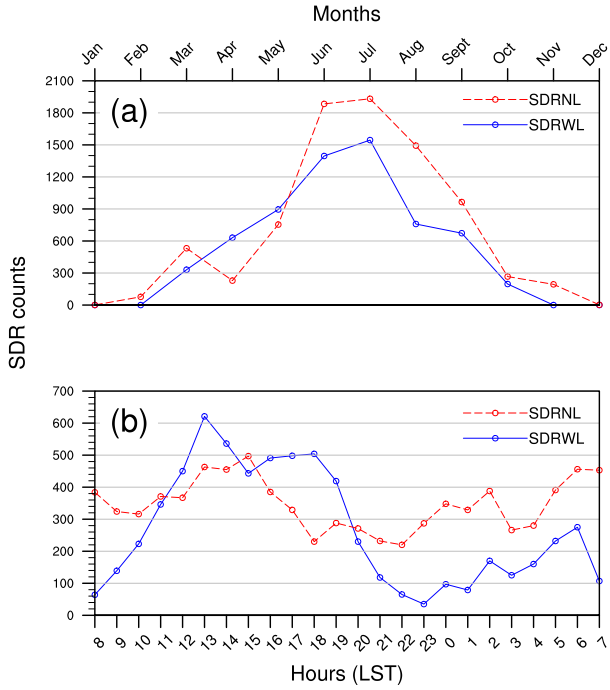

FIG. 4. (a) Monthly variation and (b) diurnal variation of SDR events with lightning (SDRWL) and SDR events with no lightning (SDRNL).

events are reported to have rainfall rates exceeding 5 mm h^{-1} (10 SDR events in Table 1 are excluded here for their rainfall rate are less than 5 mm h^{-1}), and the rainfall rate of about 50% of SDR events is greater than 20 mm h^{-1}. Moreover, the average duration of SDR events decreases with increasing rainfall rates. SDR events with the largest rainfall rate (Rate6) last only about half of those with the weakest intensity (Rate1).

The lightning flash is closely related to the strong uplifts and ice-phase microphysical processes in thunderstorms, and usually, the stronger uplifts come with a larger rainfall rate, while the accumulated rainfall is affected by much more factors. When SDR events last for a long time, even with low rainfall rates, SDR events could bring considerable rainfall. Thus, in the following sections, the lightning activity and rainfall in SDR events will be analyzed with two grading methods (amount and rate) to better understand the relationship between them.

b. *Lightning activity and rainfall during SDR events*

In 2017, 43% of 14 758 SDR events were accompanied by lightning activity in Guangzhou. As shown in Fig. 3, the average rainfall and average rainfall rate of SDR events with lightning (SDRWL) are 26.6 mm and 2.4 mm (5 min)$^{-1}$, respectively, which are significantly higher than those of SDR events with no lightning (SDRNL), whose mean rainfall and average rainfall rate are 17.8 mm and 1.7 mm (5 min)$^{-1}$. Although SDRWL often bring more rainfall than SDRNL, SDRWL usually last a shorter time than SDRNL. Results show that the average duration of SDRWL is 63.7 min, which is slightly less than the 67.1-min duration of SDRNL.

The monthly variations of both SDRWL and SDRNL (Fig. 4) show a single peak. Only a few SDR events occur in the study region in the cold seasons. In warm seasons, the amount of SDR events rapidly rises and peaks in June and July and then decreases. Of interest is that, except for April and May, in other months, the amount of SDRNL is higher than that of SDRWL, which contributes to more than half (57%) of the total 14 758 SDR events in 2017. The outnumbered SDRWL in April and May is closely related to the different environmental conditions. In April, South China is in the first rainy season when warm moist southerly flows begin to prevail, during which the lightning activity reaches its first active period in Guangzhou. Then, the South China Sea summer monsoon (SCSSM) fully breaks out and moves northward in late May. The SCSSM, the regional topography, and underlying urban surface led to the second intense period of lightning activity and significant precipitation in Guangzhou from June to August (Luo et al. 2013). Yuan and Qie (2008) studied the lightning activity before and after the onset of the SCSSM. The results show that the cell-level lightning rates in April and May are significantly higher than those in June to August, while the lightning optical radiance is lower in April and May. Although the environmental conditions in April and May are usually less favorable for strong convections than in SCSSM season, there might be more frequent but less energetic thunderstorms which can still provide considerable lightning flashes. Although both the first rainy season (April–May) and the SCSSM season (June–August) are the active periods for lightning activity, the different ratio of SDRWL to SDRNL indicates the different characteristics of thunderstorms.

More SDR events are found in the daytime according to the diurnal variation of SDR events (Fig. 4b). SDRWL show a significant diurnal variation. From 1100 to 1900 LST, the number of SDR events is much more than other periods of

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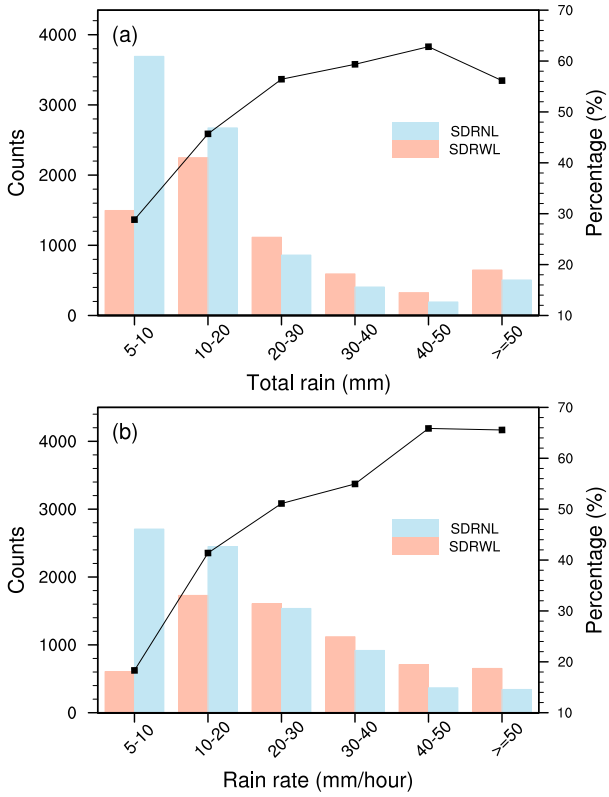

FIG. 5. Number of SDR events with lightning (SDRWL) and SDR with no lightning (SDRNL) in different (a) rainfall grades and (b) rainfall rate grades, and the proportion of SDRWL to all SDR events (polyline).

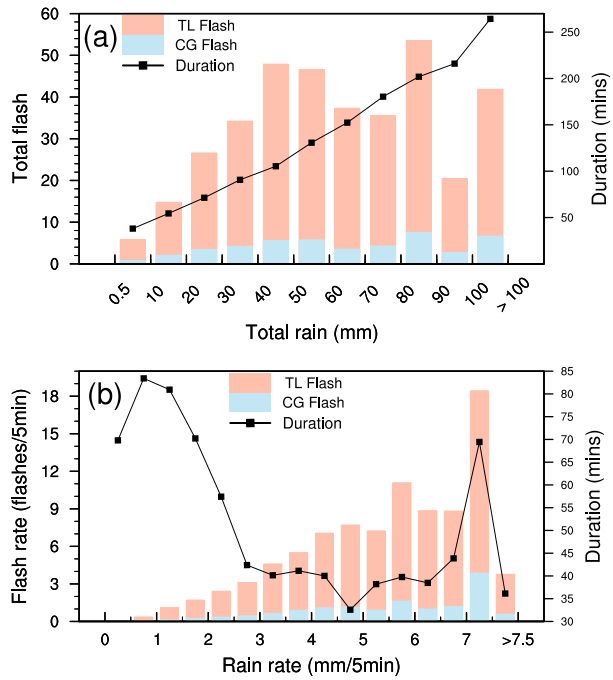

FIG. 6. (a) Mean total flash, CG flash, and duration of SDR events with different accumulated rainfall; and (b) mean total flash rate, CG flash rate, and duration of SDR events with different rainfall rates.

the day and also higher than that of SDRNL in the same period. A peak of SDRWL (about 600) occurs at 1300 LST. From 2000 LST to the next day at 1000 LST, the number of SDRWL decreases rapidly and is much lower than that of SDRNL. In contrast, SDRNL show a slight fluctuation throughout the day, with the number of 300–400, where there is no apparent diurnal variation. It has been found in the previous studies that there are much more CG flashes in the daytime than in the night over this region (Zheng et al. 2016a,b), which indicates that the underlying warming caused by solar radiation during the daytime is favorable to the development of vertical motion and deep convection systems. These conditions further lead to more lightning flashes in the daytime than the night, and a higher proportion of SDRWL.

After examining the temporal distribution of SDR events, it is desirable to examine the relationship between lightning and rainfall in SDR events with different intensities. From Fig. 5, it is clear that the proportion of SDRWL to the total SDR events increases significantly with the increase of both the accumulated rainfall and rainfall rate and only slightly decreases in the most intense grade. When accumulated rainfall is less than 20 mm (or 20 mm h^{-1}), more SDRNL are reported than SDRWL. With the increase of rainfall (rate), SDRWL outnumber SDRNL, and the highest proportion of SDRWL is close to 70%. The proportion of SDRWL in the most intense grade is about twice (by accumulated rainfall) or four times (by rainfall rate) of that in the weakest grade, indicating that lightning activity is much more frequent in the intense SDR events, especially in those with high rainfall rate.

c. *Quantitative relationship between lightning flash and rainfall in SDR events*

By grading SDRWL with finer bins, more detailed information on the relationship between lightning and rainfall can be revealed. The results show different characteristics when SDRWL are graded by rainfall (Fig. 6a) and rainfall rate (Fig. 6b). SDRWL with more rainfall last a longer time, while the case is not the same with the flash number. When rainfall is low, the average flash number in SDRWL keeps increasing as rainfall increases and reaches the first peak at 40–50 mm. After that, the average flash number slightly decreases and then meets the second peak at 80–90 mm, which is larger than the first one. Then the flash number reduces again, even in the SDRWL that last for more than 4 h and cause more than 90 mm of rainfall. It should be noted that, with the growth of rainfall, the amount of SDRWL drastically decrease, but there are still tens of events in the grade with the least number (e.g., 88 events for 90–100 mm), which is enough for representative results.

Unlike the results in Fig. 6a, there is no consistent trend of duration in SDRWL graded by rainfall rate (Fig. 6b). The SDRWL, which are less than 2.5 mm $(5\ \text{min})^{-1}$ in rainfall rate, are found to last more than 55 min and shorter with

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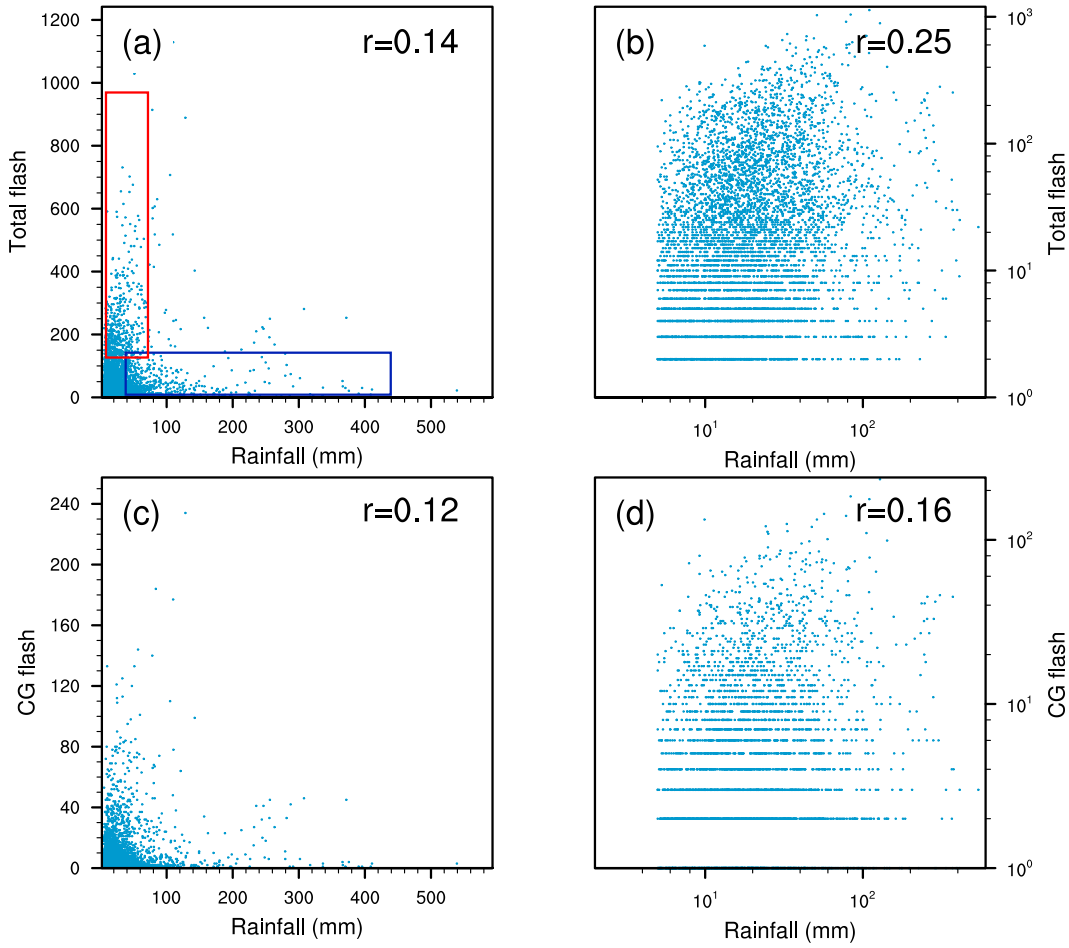

FIG. 7. Scatterplots of the (a) total flash and (c) CG flash vs rainfall in SDR events, (b) total flash logarithm, and (d) CG flash logarithm vs rainfall logarithm. The number in the upper right denotes the correlation coefficient.

higher rainfall rates. When the mean rainfall rate exceeds 2.5 mm (5 min)$^{-1}$, the average duration of SDRWL is about 40 min and varies slightly, except for the SDRWL in the 7–7.5 mm (5 min)$^{-1}$ bin, whose high duration may be caused by the small sample size (i.e., 27 events, compared with hundreds to thousands in other bins). If 7–7.5 mm (5 min)$^{-1}$ bin is excluded, a single peak can be found at 5.5–6 mm (5 min)$^{-1}$. The decrease of flash rate in the SDRWL with a high rainfall rate [more than 6 mm (5 min)$^{-1}$] indicates that lightning activity and the related ice-phase microphysical processes may be inhibited in the SDR events with extremely intense precipitation. Similar results were also found in the statistics carried by Wu et al. (2017) when examining the lightning activity in Beijing, China, using minute-level lightning and rainfall observation data. Cui et al. (2015) used numerical weather models to study the precipitation microphysics in landing tropical cyclones with different intensities. They pointed out that the collision of cloud droplets and raindrops and the melting of large ice-phase particles (graupel particles, etc.) are the two major microphysics that caused the increase of raindrop content and the occurrence of intense precipitation in landing tropical cyclones. With the increase of precipitation intensity, the microphysical processes of cloud droplet and raindrop collision increase monotonically, while the intensification of large ice-phase particles melting processes occurred earlier and then weakened in the strongest precipitation period. These findings can provide preliminary explanations for the results in this study and Wu et al. (2017), but the detailed physical processes and mechanisms need to be further revealed in future research.

From the results in Fig. 6, it can be found that SDR events with low rainfall and lightning rate last for a longer time, while the SDR events with high rainfall and lightning rate are usually shorter in duration. When examining the relationship between lightning and rainfall in SDR events, misunderstanding interpretations may be caused by the variation of flash number in SDR events with similar rainfall. Thus, the average rainfall rate and flash rate should be more appropriate to examine the relationship between lightning and rainfall in SDR events.

Pearson correlation coefficient has been widely used in the analysis of the quantitative relationship between lightning and rainfall in thunderstorms, and high linear correlation has been found in the previous studies (Petersen and Rutledge

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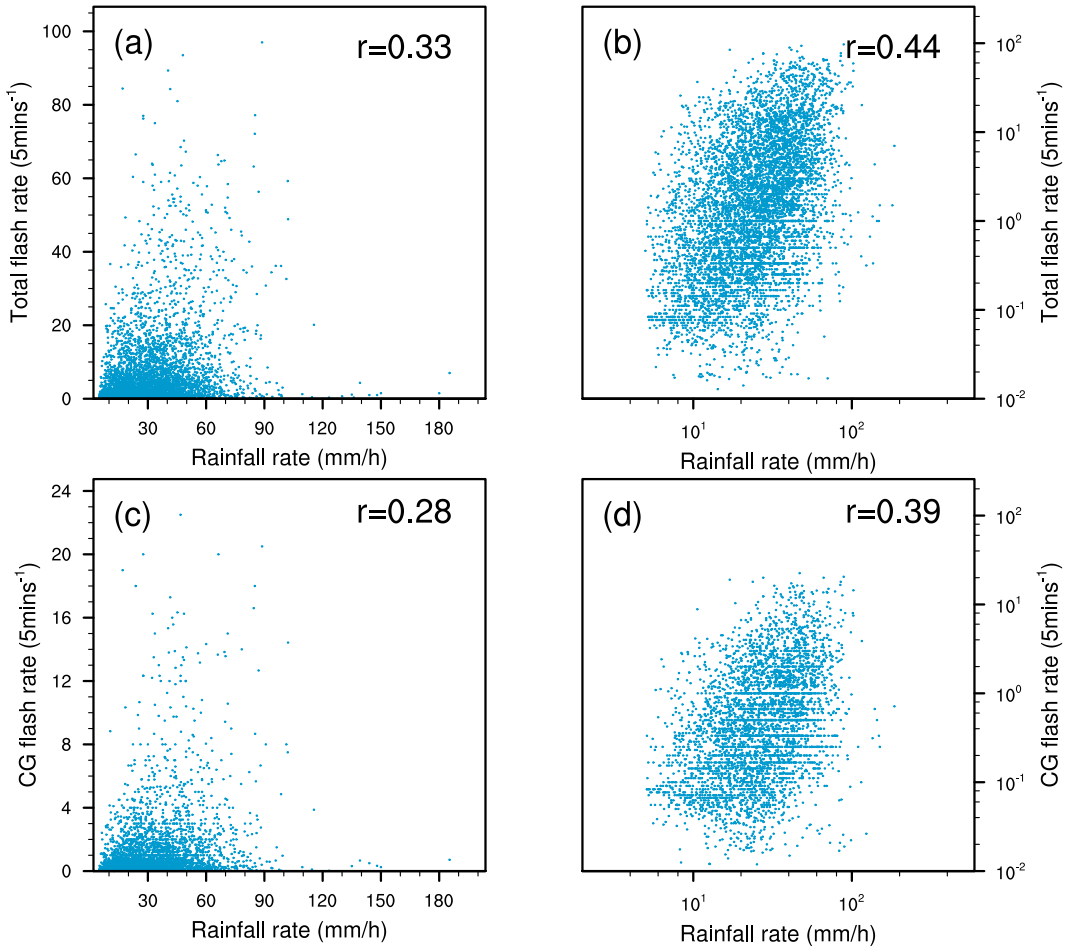

FIG. 8. Scatterplots of the (a) total flash rate and (c) CG flash rate vs rainfall rate in SDR events, (b) total flash rate logarithm, and (d) CG flash rate logarithm vs rainfall rate logarithm. The number in the upper right denotes the correlation coefficient.

1998; Piepgrass et al. 1982; Siingh et al. 2013; Soula and Chauzy 2001; Wu et al. 2017). In this study, the quantitative relationship between lightning and rainfall in 6427 SDRWL (43% of the total 14 758 SDR events) is examined, and results (Figs. 7a,c) show a poor linear correlation between the accumulated rainfall and total flash (CG flash) number with a linear correlation coefficient of 0.14 (0.12). Two kinds of SDRWL lead to the poor linear correlation between lightning flash number and rainfall. One kind of SDRWL has less rainfall but a higher flash number (denoted in the red box in Fig. 7a), while the other kind has more rainfall but a lower flash number (denoted in the blue box in Fig. 7a). A higher linear correlation coefficient is obtained between the logarithm of total flash (CG flash) number and rainfall (Figs. 7b,d), but still only 0.25 (0.16). These results indicate that a linear relationship is inadequate to represent the quantitative relationship between lightning activity and rainfall in SDRWL. Xu et al. (2013) used 13-yr TRMM observation data to examine the lightning activity and rainfall on a thunderstorm scale, and a power-law relationship was found between lightning flash rate and regional average rainfall rate. As mentioned above, mean rainfall rate and flash rate have been proved better in analyzing the relationship between lightning and rainfall. Thus, the flash rate and rainfall rate of SDRWL and their logarithm have also been examined (Fig. 8). The results show a much better linear correlation between total flash rate (CG flash rate) and rainfall rate, with a coefficient of 0.33(0.28). The correlation coefficient of logarithm flash rate and rainfall rate is 0.44 and 0.39 for total flash rate and CG flash rate, respectively. These findings indicate a nonlinear (power-law) relationship between lightning activity and rainfall in SDRWL that occurred in Guangzhou. This relationship is more explicit when flash rate and rainfall rate are used to represent the intensity of lightning activity and rainfall in SDR events, for the duration of SDRWL is included.

d. *Time-lagged correlation*

The quantitative relationship between lightning and rainfall in SDR events has been analyzed in section 3c. However, the lightning activity and precipitation in thunderstorms are not always occurring simultaneously. The searching radius used to

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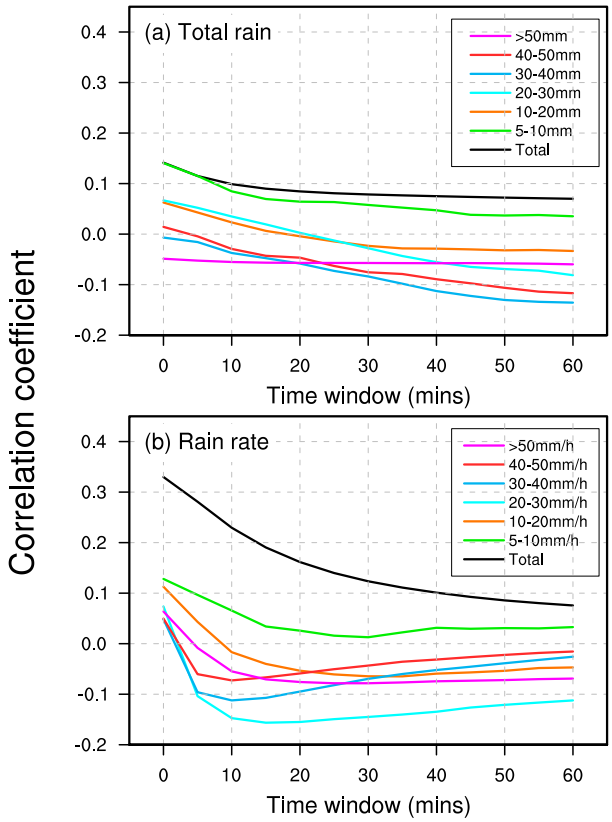

FIG. 9. (a) Variations of mean correlation coefficient between total flash and rainfall, and (b) variations of mean correlation coefficient between total flash rate and rainfall rate in SDRWL with time window of 0–60 min.

match lightning and rainfall can also lead to the time lag between lightning and rainfall. Thus, it is necessary to examine the correlation between lightning and rainfall with extended time windows because there might still be considerable lightning flashes outside the duration of SDR events. The correlation coefficients are calculated with time windows ranging from 0 to 60 min before and after the SDR duration. The overall extended correlation coefficient of rainfall and flash number in SDRWL show a flattened curve with different time windows and decrease slightly when time windows increase (Fig. 9a). However, the correlation coefficients in SDRWL with different rainfall respond differently to time windows. The correlation coefficient of SDRWL with rainfall higher than 50 mm and lower than 20 mm changes little with time windows. In contrast, the correlation coefficients in SDRWL with rainfall from 20 to 50 mm decrease rapidly when time windows increase. This difference indicates that there are still numerous lightning flashes out of the duration of SDRWL with a rainfall of 20–50 mm, but the number of these "outside" flashes is poorly proportioned to the accumulated rainfall of SDRWL, which leads to the decrease of correlation coefficients with increasing time windows. More obvious variation can be found in the correlation coefficients between flash rate and rainfall rate (Fig. 9b). The overall correlation coefficient decreases from more than 0.3 to about 0.1 when the time window increases to 60 min. A similar decrease can also be found in graded SDRWL, except for SDR events with a 5–10 mm h^{-1} rainfall rate (Fig. 9b). Namely, correlation coefficients decrease the most rapidly in the time windows of 0–20 min and then gradually reduce to about zero when time windows further grow. This variation indicates that the most of the "outside" lightning flashes occurred 0–20 min before and after the SDR events. More irrelevant lightning flashes are matched with the SDR events with larger time windows, which leads to poor correlation coefficients. It is worth noting that, with the extended time window, negative correlation coefficients can be found in Fig. 9b, and the absolute values of the correlation coefficients are even higher than those with no time lag. These abnormal values are caused by the grading of SDRWL and the extended time windows. On the one hand, grading will lead to fewer differences in rainfall rate between SDR events in the same grade, which will significantly reduce the correlation coefficients with zero lag. On the other hand, with the extension of time windows, the lightning rate and rainfall rate of SDR events with intense lightning activity and precipitation out of the duration will be much higher than the average, which contributes to the high negative correlation coefficients. Although negative correlation coefficients can be found in several grades, it does not mean that the decrease of rainfall rate accompanies the increase of lightning rate because even with a 60-min time window, the overall correlation coefficients remain positive (Fig. 9b).

The time-lagged correlation coefficients between total flash rate and rainfall rate within ±60 min before and after SDRWL duration are further calculated (Fig. 10). The results show that the max time-lagged correlation coefficients are found when lightning lagged precipitation for 5–10 min in SDRWL with any intensity. However, the distributions of max time-lagged correlation coefficients are not exactly the same in SDR events with different rainfall rates. In weak SDR events (rainfall rate less than 5–30 mm h^{-1}), the correlation coefficients decrease greatly with the increase of positive time lag, while slightly with the decrease of negative time lag. Moreover, when time lag is positive, correlation coefficients are mostly negative but turn to positive when time lag is negative. In SDR events with high rainfall rates (≥30 mm h^{-1}), correlation coefficients decrease rapidly when time lag departs negatively or positively from the range of 5–10 min. The coefficients with positive time lag are slightly higher than those with a negative time lag. These results show that although the 5–10 min of lightning lagging precipitation is expected in SDR events with any rainfall rate, this relationship is more stable in the SDR events with higher intensity. Namely, the lightning activity is more likely to lag precipitation in SDR events with a high rainfall rate.

To further examine the time-lagged correlation between lightning activity and precipitation in SDRWL, the max time-lagged correlation coefficients, the start time and peak time difference between lightning and precipitation are calculated for all (Fig. 11) and graded SDWL (Fig. 12). Similar distributions

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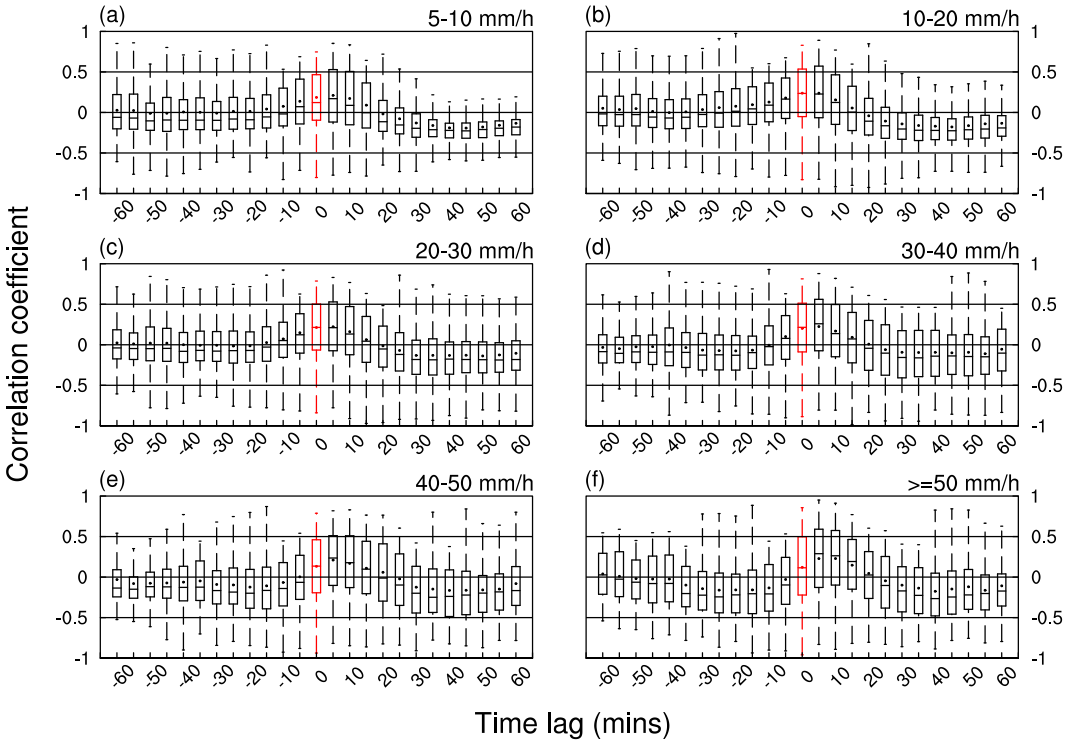

FIG. 10. Time-lagged correlation coefficients between total flash rate series and rainfall series in SDR events with rainfall rate of (a) 5–10, (b) 10–20, (c) 20–30, (d) 30–40, (e) 40–50, and (f) ≥50 mm h^{-1}; negative time lags denote that the lightning series precedes the rainfall series.

are found in max time-lagged correlation coefficients and peak time difference (Figs. 11a,b). About half of SDRWL are found with a time lag from −5 to 20 min (positive lag means precipitation precedes lightning), and the peak occurred at 5 min. The start time difference shows a lower peak (Fig. 11c). The number of SDRWL in which precipitation starts earlier than lightning is much more than that of lightning precedes precipitation, and the largest number of SDRWL occurred at 10 min. This even distribution of start time difference indicates the temporal relationship between the start time difference between lightning activity and precipitation in SDR events is not as stable as that of the peak time. Table 3 shows the percentage of SDRWL in which lightning series are preceded, lagged, and occurred at the same time with precipitation. The results show that there are about 55% of SDRWL with precipitation preceding lightning, while precipitation lagging lightning is found in about 35% of SDRWL, and in about 10% of the SDRWL, lightning activity and precipitation occur at the same time. These results are different from those in the previous studies. For example, Koutroulis et al. (2012) examined 16 rainfall events and found that the lightning activity within 15 km around the rain gauges reaches the max correlation coefficients with the rainfall 15 min later. Wu et al. (2017) used 2-yr lightning observation to analyze the relationship between lightning and rainfall in summer SDR events, and lightning activity in about 50%–60% of the SDR events was found to precede precipitation. There are also studies indicating that lightning activity can occur later than precipitation. Gungle and Krider (2006) found an average of 20 min that the lightning occurred before the rainfall in six thunderstorms in Florida, while in another thunderstorm, the rainfall was reported to precede the lightning by 5 min. Several explanations about these results are that, first, the matching method of lightning and rainfall in these studies can be quite different. For example, a 15- and 10-km searching radius is used in the study of Koutroulis et al. (2012) and Wu et al. (2017), respectively. As introduced in section 2b, a 5-km searching radius is used in this study for the densely distributed AWSs. A larger searching radius can provide earlier lightning information at a far distance, especially in thunderstorms with high moving speeds. Thus, in the studies with a large searching radius, lightning activity is more likely to be reported to occur before the precipitation. Second, the previous studies mostly focused on the lightning and rainfall in strong thunderstorms. In this study, the relationship between lightning and rainfall for the entire year is examined, and the observation data were not selected with precipitation types or seasons, which may also lead to differences in the results. Moreover, the study region (Guangzhou) lies on the south coast of China, where the regional effects and local weather conditions may contribute to the unique characteristics of lightning activity.

The time-lag characteristics of SDRWL with different intensities are also calculated. Both the max time-lag

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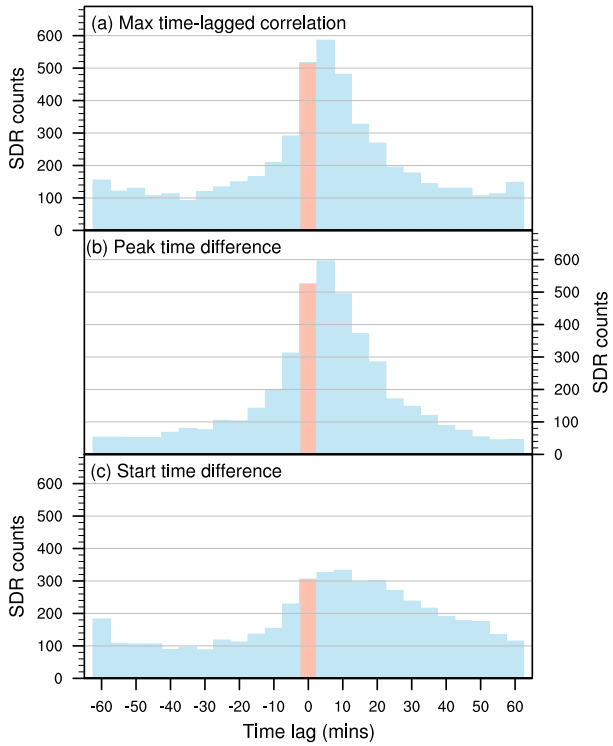

FIG. 11. Number of SDR events (a) achieving max time-lagged correlation coefficients, (b) peak time difference, and (c) start time difference between lightning and precipitation in SDR events with ±60-min time lag; negative time lags denote that the lightning series precedes the rainfall series.

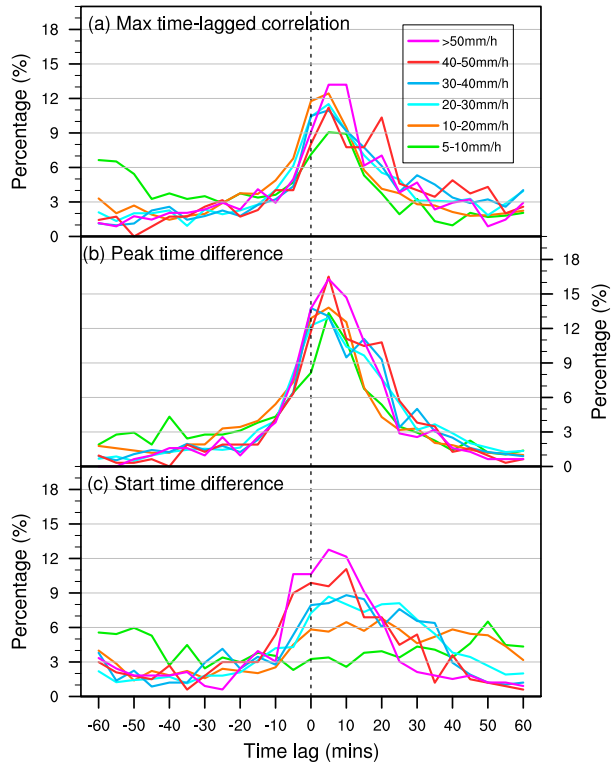

FIG. 12. Proportion of (a) max time-lagged correlation coefficients, (b) peak time difference, and (c) start time difference between lightning and precipitation in SDR events with different intensity with ±60-min time lag; negative time lags denote that the lightning series precedes the rainfall series.

correlation coefficients and peak time difference of graded SDRWL show a single peak at 5–10 min (Figs. 12a,b). That is, the centralized distributions in Figs. 11a,b can also be found in SDRWL with any intensity. Most of the max time-lag correlation coefficients and peak time difference occur from −10 to 20 min. Of slight difference is that the peak time difference distributions of SDRWL (Fig. 12b) share similar curves, while the curves of max time-lag correlation flatten in SDRWL with low rainfall rate (Fig. 12a). The start time difference is closely related to the rainfall rate intensity (Fig. 12c). For SDRWL with lower rainfall rates (i.e., 5–20 mm h^{-1}), the start time difference separately distributes with time lag ranging from −60 to 60 min. With the increase of rainfall rate, a higher proportion of SDRWL concentrates in the range from −10 to 20 min. From these results, we can conclude that the temporal relationship between lightning activity and precipitation in SDR events is quite complicated. In heavy SDR events, lightning and precipitation tend to occur with short time lags, ranging from −10 to 20 min. While in weak SDR events, lightning can occur almost any time in one hour before and after precipitation. The distribution of peak time difference and lagged correlation are more concentrated. The lightning flash rate peak is most likely to be found from −10 to 20 min after the rainfall rate peak, and this relationship varies slightly with intensity.

4. Conclusions and discussion

In this study, the ENTLN lightning observation over Guangdong province and the rainfall data derived from Guangzhou automatic weather stations in 2017 are analyzed to examine the quantitative and temporal relationship between lightning activity and rainfall in 14 758 (14 748 when graded by rainfall rate) SDR events, and the major results are as follows:

The average annual SDR rainfall of 2017 over Guangzhou is about 2000 mm, and a topography effect has been found in the spatial distribution of annual rainfall. The mean total flash density is about 10 flashes km^{-2} yr^{-1}. In 2017, there were 14 758 SDR events reported on 270 AWSs, and the average is 54. The average duration of SDR events is found to increase with increasing accumulated rainfall but decreases with the increasing rainfall rate.

TABLE 3. Proportion of SDR events in which lightning precedes, lags, and coincides with precipitation in max correlation coefficient, peak time difference, and start time difference.

	Preceding (%)	Lagged (%)	No time lag (%)
Max r	35.0	54.9	10.1
Peak time	30.0	57.8	12.2
Start time	33.1	60.2	6.7

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The results show that about 43% of the SDR events are accompanied by lightning activity, and the accumulated rainfall and rainfall rate of these SDR events are significantly higher than those with no lightning. More SDR events are reported in the warm seasons than the cold seasons, and the peak occurs in July. A high ratio of SDRWL to SDRNL is found in April and May, which is closely related to the different environmental conditions for convections before and after the breakout of the SCSSM in late May. The diurnal variation of SDR events shows that SDR events are more likely to occur in the daytime, especially afternoon hours. The number of SDRNL fluctuates through the day to a limited extent, while SDRWL show an apparent diurnal variation of SDRWL. SDR events are more likely to occur in night hours with no lightning. In contrast, the outnumbered SDRWL in afternoon hours indicate that solar radiation is critical for lightning activity over this region.

The ratio of SDRWL to SDRNL increases significantly with SDR intensity. This ratio in heavy SDR events can be 2–4 times than in weak. The results also show that the flash rate in SDR events does not monotonically increase with the rainfall rate. The flash rate is found to decrease in SDR events with extreme rainfall. The correlation coefficient between flash rate and rainfall rate in 6427 SDR events shows a moderate (0.33) positive correlation. This correlation coefficient is higher (0.44) between flash and rainfall rate logarithm, indicating a power-law relationship.

Generally, the lightning series in SDRWL lags precipitation for 5–10 min in SDRWL, and this lag is more obvious in heavy SDRWL. Lightning is found to precede precipitation in more than 35% of SDRWL and lag precipitation in about 55% of SDRWL. About half of SDRWL obtain max time-lagged correlation coefficient and peak time difference when lightning is lagged from −10 to 20 min. This distribution varies slightly in SDR events with different rainfall rates. The start time difference is closely related to the intensity of SDRWL. In weak SDRWL, lightning can start at any time in 60 min before or after precipitation. With the increase of intensity, lightning is more likely to occur after precipitation from −5 to 20 min.

Based on the above results, we may conclude the following: (i) The characteristics of SDR events with lightning activity are different from those with no lightning, including but not limited to precipitation intensity and diurnal variation. (ii) The quantitative relationship between lightning flash and rainfall in SDR events is complicated, and a power-law relationship is found to describe better the lightning and rainfall in SDR events over Guangzhou. (iii) The time relationship between lightning activity and precipitation is related to the intensity of SDR events. Lightning is more likely to occur before and after precipitation with a short lag (i.e., 10–20 min) in heavy SDR events.

Lightning activity and precipitation result from the complex thermodynamic, microphysical, and electrical processes inside thunderstorms. Previous studies have shown that the convection initiation and growth over South China are closely linked to numerous factors, such as the boundary layer jet, terrain, coastline, and cold pools (Du et al. 2020a,b). And the extreme precipitation over this region is accompanied by a broad range of convective intensity (Yu et al. 2022). These studies revealed that the relationship between lightning and precipitation over South China is much complicated, which could be affected by numerous factors. More observational and numerical studies should be carried out to better understand the relationship and associated mechanisms behind it, as well as to reveal its differences with other regions worldwide.

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Data availability statement. Due to its proprietary nature, the minute precipitation observation at meteorological stations and the ENTLN lightning observation from the Guangdong Meteorological Service cannot be made open. Further information about the data and conditions for access is available at http://data.cma.cn/en. All the data analyzed in this study can be downloaded from https://pan.cstcloud.cn/s/w0XVp9qCSCM to reproduce the results of this study.

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