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Key Points:
- Physical and observable characteristics of CG lightning were deduced from LLS
- Observation based methodology was used to increase understanding of lightning
- CG lightning was studied on five typical microenvironments in the PRD region

Supporting Information:
- Readme
- Figures S1–S10 and Tables S1–S3

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Physical and observable characteristics of cloud-to-ground lightning over the Pearl River Delta region of South China

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Abstract Cloud-to-ground (CG) lightning characteristic parameters deduced from the lightning location system (LLS) for five differing microenvironmental areas relative to megacity, city, municipal town, hilly suburban area, and mountainous rural area conditions were examined in our 2009–2011 Pearl River Delta (PRD) study. Our LLS data analysis showed that there were high variation of lightning characteristics and phenomenal changes among these areas. As a supplement to the usual study of physical characteristics, an observation-based methodology had been developed to study the lightning behavior, while the respective thunderstorms were traversing through these observation areas. Special features and phenomenal changes related to the lightning characteristic parameters, such as observable lightning stroke days (OLSDs) and observable lightning stroke frequency and density for an OLSD, were also addressed. Microenvironmental variation due to change in topography, degree of urbanization, urban effect, and thunderstorm strength was found to affect the spatial distribution of lightning stroke and the severity of lightning activities over the observation areas. This approach increases our understanding of lightning in subtropical China. It also tells us more about the behavior of lightning while the thunderstorm traverses through an observation area. This information is lacking in previous studies.

1. Introduction

Following the development of advanced lightning detection tools and methods, as well as the utilization of lightning location system (LLS), thunderstorm activities and cloud-to-ground (CG) lightning characteristics in various areas throughout the world were increasingly studied. LLS has been providing real-time lightning information in USA (National Lightning Detection Network, NLDN) as early as the late 1970s [*Orville*, 1991]. In China, LLS (lightning location system of China Power Grid) began to set up in the late 1980s [*Chen et al.*, 2008, 2010]. As described in the next section, this LLS has high detection efficiency. It has been incorporated into large part of China and provides a platform for the study of lightning activity as well as for the detection of lightning location, quantification, prewarning, protection and analysis, observation, and investigation [*Chen et al.*, 2010].

Studies found lightning enhancement in large urban areas of USA, Brazil, and India [*Chaudhuri and Middey*, 2013; *Pinto et al.*, 2004; *Steiger et al.*, 2002; *Westcott*, 1995]. A significant enhancement in the number of negative CG (−CG) lightning and a decrease in the percentage of positive CG (+CG) flashes were found over the city of São Paulo [*Farias et al.*, 2009]. Small urban areas also can enhance CG lightning [*Soriano and de Pablo*, 2002]. Other studies found evidence of thermal, aerosol, and geographic impact on CG lightning physical properties. Modification of lightning density and polarity happened over large urban areas of southeastern Brazil [*Naccarato et al.*, 2003]. Aerosols played a major role in enhancement in lightning activity over two inland metropolitan cities of India [*Lal and Pawar*, 2011]. Weekend-weekday aerosols and geographic variability affected CG lightning in Atlanta, USA [*Stallins et al.*, 2013]. *Ashley et al.* [2012] performed a climatological synthesis to show how urbanization augmented warm-season convection among a range of cities via high-resolution radar reflectivity in southeastern U.S. *Andreae et al.* [2001] provided evidence to show the importance of deep convection in the equatorial region as a mechanism to transport large amounts of pyrogenic pollutants into the upper troposphere. The effect of smoke on convection, including the possibility of enhancing CG lightning, had also been discussed. *Lang and Rutledge* [2006] provided support that smoke aerosols impact CG polarity and suggested that there is a possible link between drought conditions and increased +CG percentage. *Kochtubajda et al.* [2011] pointed out the relationship between the 2004 lightning season and wildfire activity in Yukon, Canada. Also, lightning and climate was reviewed by *Williams* [2005].

In China, researches on lightning were mainly focused on lightning physical processes, lightning mechanisms, lightning detection, lightning warning, and lightning protection [*Qie et al.*, 2006]. Lightning characteristics had been studied in Beijing, Tibet Plateau, and Guangdong [*Chen et al.*, 2004; *Qie et al.*, 1991, 2002]. Both natural lightning and artificial-triggered lightning had been used to study the physical processes of lightning and electric charge structure of thunderstorm [*Lü et al.*, 2012; *Qie et al.*, 2006, 2009; *Zhang et al.*, 2014]. However, observation-based investigation of lightning activities and characteristics for the Pearl River Delta (PRD) region and other regions in China has not been performed.

In this paper, data acquired from the South China Power Grid LLS which had been upgraded twice since it came into operation in 1997 were used. We chose five representative areas covering 10 km radius of five selected observation points relative to megacity, city, municipal town, hilly suburban area, and mountainous rural area conditions for our 2009–2011 PRD study. We first examined the physical lightning characteristic parameters deduced from LLS data for the five observation areas. Then, an observation-based methodology was developed and used to study phenomenal changes in lightning activities, while the respective thunderstorms were traversing though these observation areas. This methodology was employed to explore the linkage between the observed phenomenal changes, especially whether lightning was severe, intensive, or dispersive, and corresponding changes in lightning characteristic parameters including observational ones.

2. The South China Power Gird LLS and Performance in PRD

In brief, the LLS in the PRD region is a part of the Guangdong (GD) LLS setup. It initially consisted of 11 combined time-of-arrival/magnetic direction finder (TOA/MDF) sensor (TDF-2000, Wuhan, China) stations in 1997. The sensor station raw data were collected by the naval process apparatus. It was then analyzed and stored in the lightning location information analyzer and display system. Five LLS sensor stations were added in May 1999. After the 1999 upgrade, the detection efficiency for CG lightning flash was about 86% with an average location error approximately 1300 m [*Chen et al.*, 2002]. Multistation observation technique was then used to increase the accuracy of detecting flashes position and the sensitivity of detecting lightning flashes. For example, different detection stations distributed in a large domain have been used to identify the lightning signal and perform real-time location calculation using the same criterion. Stations that do not satisfy the criterion are not used in the location calculation [*Chen et al.*, 2010]. The LLS sensor (TDF-2000, Wuhan, China) stations were upgraded again in 2007–2010, and the number of sensor stations was also increased to 27. The GD LLS was then integrated into the China Power Grid system in 2010. The detection efficiency of individual lightning flash was then found to be greater than 90%, and the location precision is about 0.5 km [*Chen et al.*, 2010]. The sensitivity and location accuracy improved considerably near the edges of the GD network with the addition of 11 more LLS sensor stations during this period. Also, based on rocket-triggered lightning experimental data in Conghua of GD from 2006 to 2011, it was found that the LLS yielded flash detection efficiency of 92% and the location error was up to 760 m [*Zhang et al.*, 2014]. In 2011, there were six sensor stations in the PRD region and another five sensor stations in its outskirt. The distance between most of the adjacent sensor stations is about 150 km (Figure 1). Multistation observation showed that more than 95% of CG lightning data during the observation period were recorded by more than three senor stations. Now the minimum detected peak current is about 1 kA. This improves detection of small flashes. Most sensor stations are located on flat area or surrounded by low terrain. Such arrangement can reduce error induced by the terrain effects which limits signal propagation. So over our observation period 2009–2011, the LLS in the PRD region had about 90% flash detection efficiency and less than 800 m location error.

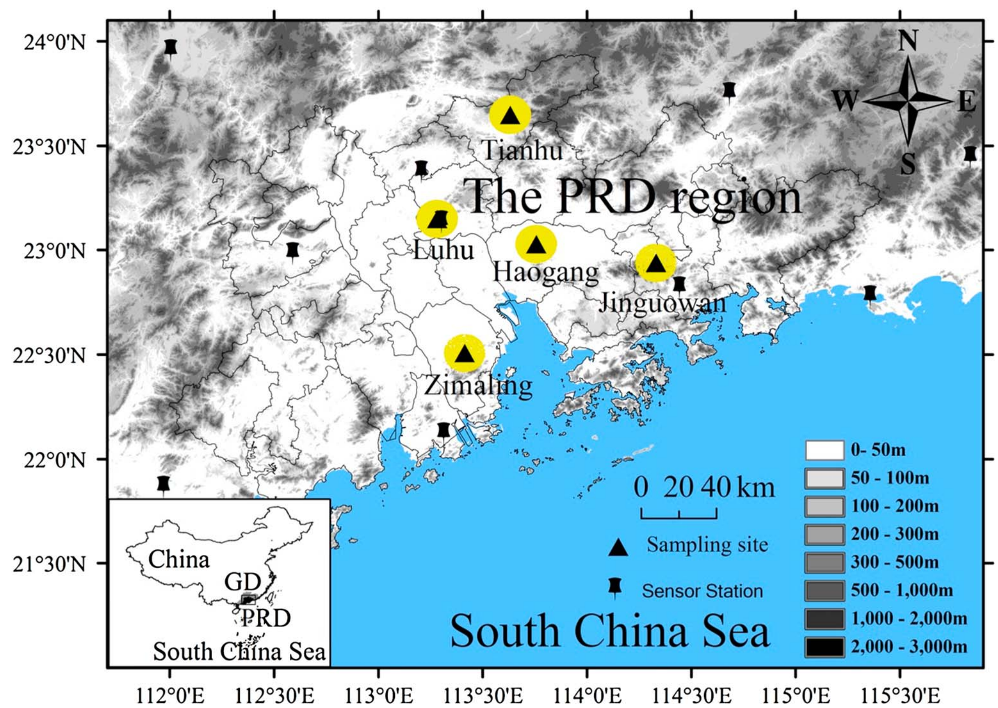

Figure 1. Topography of the PRD region and location of the five observation areas (Luhu, Haogang, Zimaling, Tianhu, and Jinguowan) and LLS sensor stations in the PRD region, South China. (The five CG lightning observation areas are all in respective circles.)

3. Observation Area Characteristics

The PRD region of South China occupies an area about 41,700 km^2. It is over 80% urbanized (http://roll.sohu.com/20130314/n368736897.shtml) and densely populated [*Chan and Yao*, 2008]. A description of the PRD region characteristics is given in the supporting information (SI). PRD is under the control of the subtropical monsoon climate, and high number of thunderstorms and lightning flashes are found in months from April to September which are also the hottest months of the year in this part of China [*Zhang et al.*, 2000]. Thunderstorm is active in the PRD region from May to September. It is closely associated with the rainy season from April to September. There are two rainy seasons [*Ding and Wang*, 2008]. The first rainy season (or presummer rainy season) occurs in April–June, and it is dominated by the midlatitude weather system. The second rainy season (or post flooding season) occurs in July–September, and it is dominated by tropical cyclones and other tropical weather systems. The dates of occurrence and the intensity of the thunderstorms are greatly affected by the early or late onset and early or late ending of these two rainy seasons. In this study, lightning was found to occur mostly in months of May, June, and July, and the lightning activity in the whole region was closely related to the climatic condition in South China.

Apart from high frequency of lightning activities associated with onset of the monsoon season, the PRD region in South China also features high variation in topography, in degree of urbanization, in urban size and structure, in population, in thunderstorm strength as well as in land and sea impact. Many typical microenvironments exist. Their effects on lightning activities and lightning characteristics are noteworthy. This view is supported by our LLS data analysis which showed that there were high variation of lightning characteristics and lightning phenomenal changes in various areas of the PRD region. The topography of the PRD region, the location of the five observation areas, and the location of the LLS stations are shown in Figure 1. We further demonstrate our point of view with the illustration in Figure 2 which is the lightning flash density plot in Guangdong province from 2009 to 2011. In this plot, the lightning flash data were placed into grids of approximately 0.1° longitude and 0.1° latitude, corresponding to an approximate resolution of 10 km, similar to the grid used in previous study by

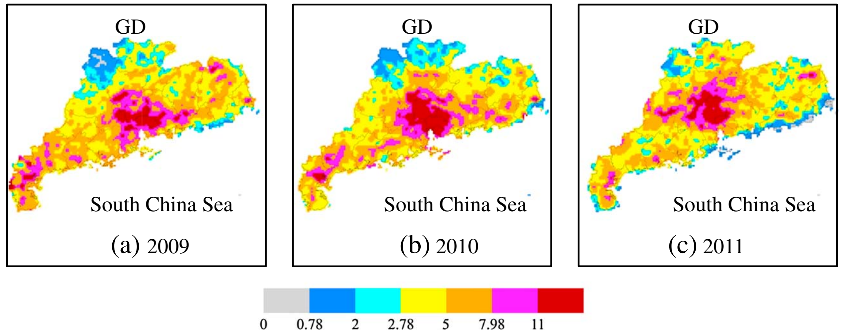

Figure 2. Average geographical distribution of flash density (fl km^{-2} yr^{-1}) in Guangdong (GD) province for the period 2009–2011: (a) 2009, (b) 2010, and (c) 2011.

Rudlosky and Fuelberg [2010] for the Contiguous United States. We found that the lightning flash densities in the PRD region were high and also with high variation in different areas.

In this study, all analyses referred to an observation area which is the area within 10 km radius of a selected observation point. LH, HG, ZML, JGW, and TH are used to represent observation areas. Relevant information is presented in Table 1, and the observation areas are described briefly below:

1. LH (Luhu Park) is located in megacity Guangzhou, with a population of 12.75 million (2011), and about 150 km away from the South China Sea. In 2005, it was reported that there were more than 7000 high buildings which were higher than 18 floors (about 50 m) in Guangzhou (http://sy.house.sina.com.cn/news/gddt/2005-04-07/10412258.html). In 2011, there were 341 super high buildings which were more than 100 m high (http://top.gaoloumi.com, the same below).
2. HG (Haogang primary school) is located in an industrial city Dongguan, with a population of 8.22 million (2011), and about 100 km away from the sea. Compared to Guangzhou, the high building (mostly between 50 m and 100 m) number was lower. There were 16 super high buildings over 100 m high in this city.
3. ZML (Zimaling Park) is within a municipal town in Zhongshan, with a population of 3.14 million (2011), and about 60 km away from the sea. The number of super high building over 100 m high was 6. The height of other buildings was mainly below 50 m.
4. JGW (Jingguowan Ecological Farm) is located in a hilly suburban area in Huizhou and close to the sea (about 50 km).
5. TH (Tianhu Park) is located in a rural area in the northeast of Guangzhou and about 190 km away from the sea. It is an important place connecting the PRD region with the mountainous area in the north of Guangdong province. Its southwest is plain and its north and northeast is highland (height: 200–600 m) (Figure 1).

4. Lightning Data and Observation-Based Analysis Methodology

CG lightning data from the LLS were supplied by State Grid Electric Power Research Institute (Wuhan, China), and the lightning data corresponding to different stages of the upgrade had been carefully weighted and adjusted so that lightning statistics can be compared under one unified standard. Data coverage is

Table 1. Information for the Five Observation Areas in the PRD Region

No.	Observation Point	Location	Observation Area Type	Altitude (ASL) (m) / Distance From the Sea (km)
LH	Luhu Park, Guangzhou	E113.282° N23.149°	Megacity urban area, plain	30/150
HG	Haogang primary school, Dongguan	E113.757° N23.028°	City urban area, plain	28/100
ZML	Zimaling Park, Zhongshan	E113.414° N22.507°	Municipal town urban area, plain	45/60
JGW	Jinguowan Ecological Farm, Huizhou	E114.331° N22.939°	Suburban area, low elevation hill, close to the sea	77/50
TH	Tianhu Park, Conghua	E113.632° N23.648°	Rural area, high elevation mountain area, far from the sea	251/190

Table 2. CG Lightning Characteristics of the Five Observation Areas in PRD, 2009–2011

No	OLSD (D yr^{-1})	Stroke Density[a] (str km^{-2} yr^{-1})	Flash Density[b] (fl km^{-2} yr^{-1})	Lightning Type[c]	Strokes (str yr^{-1})	P (+)[d] (%)	Mean Peak Current (kA)	Mean Stroke Number (fl^{-1})
LH	113.3 ± 12.5	39.5 ± 3.4	19.8 ± 3.4	+	833.7 ± 171.4	6.72 ± 1.15	23.86 ± 0.43	1.06 ± 0.01
				−	11579.0 ± 963.9		31.38 ± 0.12	2.13 ± 0.02
HG	112.0 ± 18.3	45.9 ± 15.4	23.0 ± 8.5	+	1067.3 ± 369.1	7.41 ± 0.18	25.05 ± 0.47	1.07 ± 0.01
				−	13330.3 ± 4464.5		32.09 ± 0.13	2.14 ± 0.02
ZML	103.3 ± 11.2	22.6 ± 11.4	12.3 ± 6.0	+	754.0 ± 290.9	10.64 ± 1.28	28.14 ± 0.60	1.09 ± 0.01
				−	6334.0 ± 3294.5		34.82 ± 0.27	1.99 ± 0.03
JGW	142.0 ± 18.3	23.9 ± 10.8	15.5 ± 6.7	+	593.7 ± 207.8	7.90 ± 2.54	21.71 ± 0.54	1.05 ± 0.01
				−	6919.3 ± 3215.7		24.02 ± 0.17	1.61 ± 0.03
TH	102.0 ± 18.3	27.7 ± 8.8	13.0 ± 3.6	+	530.3 ± 165.8	6.09 ± 0.23	27.10 ± 0.54	1.06 ± 0.01
				−	8177.3 ± 2586.1		28.53 ± 0.14	2.28 ± 0.02

[a]Lightning stroke density calculation method: number of observed lightning strokes from April to September averaged over 2009–2011 per square kilometer per year.
[b]Lightning flash density calculation method: number of observed lightning flashes from April to September averaged over 2009–2011 per square kilometer per year.
[c]Lightning type: +CG lightning (+) and −CG lightning (−).
[d]P (+): percentage of +CG lightning.

continuous. In China, flash detection efficiency was used to estimate the LLS detection efficiency [*Chen et al.*, 2010]. We followed this approach and used flash in the analysis of physical characteristics of CG lightning. The data given by the LLS allow characterizing the CG activity with the following parameters: the location of each CG lightning flash, occurrence time, polarity, number of flashes, number of strokes (multiplicity), and peak current of the strokes for each flash.

In the observation-based analysis, the focus was on an area within 10 km range (this range was also used in another study [*Sonnadara et al.*, 2006]) of the five observation points in the PRD region during April to September 2009–2011. Lightning strokes were used in this methodology, because it gives better interpretation on lightning behavior over the observation areas. Paths of thunderstorm that traversed the observation areas representing specific microenvironmental conditions of interest and the corresponding lightning stroke variation with time were constructed utilizing the LLS data. We inputted the CG lightning locations and time into the software ArcGIS (Version 9.3, ESRI, USA) and used the “tracking analyst” extended module to generate pictures of successive appearance of 10 min strokes in the observation area. Lightning strokes appearing in every 2 of the 10 min in the past were color coded differently in each of these pictures. Picture after picture, the thunderstorm path was illustrated. This basic tool was then used for the observation-based analysis. This approach can improve the understanding of lightning activities over small area or large region. It can also further illustrate special features and findings that were missed in past studies. In particular, we had used this methodology to reveal specific physical features and phenomenal lightning distribution scenarios in these observation areas that cannot be addressed by statistical analysis in *Sonnadara et al.* [2006] and *Steiger et al.* [2002] and large urban/city domain analysis approach in *Coquillat et al.* [2013]. In the present study, 150,357 lightning strokes (or 78,832 lightning flashes) had been analyzed.

5. Results and Discussion

The mean peak current of the strokes, strokes for each flash, observable lightning stroke day (OLSD, the local calendar day with at least one lightning stroke observed within the observation area), annual lightning stoke frequency, the mean number of strokes (multiplicity) per flash, annual lightning stroke density, and annual lightning flash density for the lightning events over the observation areas are presented in Table 2.

5.1. General Physical Properties of Lightning in PRD

For the five observation areas of the PRD region, both −CG and +CG lightning strokes were found in the lightning events (Table 2). During the sampling period, the average annual total number of strokes for −CG and for +CG lightning were 46,340.0 ± 10,828.7 and 3779.0 ± 820.9. The fluctuation of number of strokes for the five observation areas was large. Average peak currents of observed −CG and +CG lightning stroke were −30.4 ± 0.1 kA and +25.2 ± 0.2 kA, respectively. The peak currents of hilly suburban JGW were much lower (+21.71 ± 0.54 kA, −24.02 ± 0.17 kA) compared to megacity LH (+23.86 ± 0.43 kA, −31.38 ± 0.12 kA). A lightning flash may include several strokes, and the multiplicity was studied here. The average number of strokes per flash for the five observation areas was close (2.03 ± 0.26 for −CG lightning and 1.07 ± 0.02 for +CG lightning). The highest numbers of strokes per −CG and +CG lightning were 17 and 4, respectively. It is noted that 60.4% and 93.7% of −CG and +CG lightning flashes were with one stroke. Also, we found that the percentage of +CG lightning (P (+)) for the observation areas close to the sea (8.6–11.9%) was higher than for those far from the sea (6.5–8.0%). Compared with the P (+) in Tibetan Plateau (16%) [*Qie et al.*, 2002], Lanzhou (9.2%) [*Qie et al.*, 1991], and Beijing (10.9%) [*Zhang et al.*, 2010] in the northern part of China, or in the Japan sea coast in winter (50–60%) [*Hojo et al.*, 1989], the P (+) in the PRD region was lower. The high percentage (>90%) of −CG lightning suggests that the thunderstorm cloud structure in the PRD region was dipolar (the top and bottom of the thunderstorm clouds were mainly of positive charge and negative charge). *Orville* [1991] found that the density of the negative electricity for this kind of thunderstorm was an order of magnitude larger than that for positive electricity. Thunderstorm cloud structure in the southern part of China was different from that in the northern part of China [*Zhang et al.*, 1997]. The thunderstorm clouds in north China were mainly tripolar in structure with the top and bottom of the cloud positively charged and the middle negatively charged [*Zhang et al.*, 2000].

5.2. Observation-Based Investigation of Lightning Activities in the Five Microenvironmental Areas

5.2.1. Observable Lightning Characteristics for the Five Microenvironmental Areas

From Table 2, we observe that the highest annual OLSDs occurred in the hilly suburban area (JGW 142.0 ± 18.3 days (D)), medium OLSDs in the urban areas (LH 113.3 ± 12.5 D, HG 112.0 ± 18.3 D, and ZML 103.3 ± 11.2 D), and the lowest OLSDs in the mountainous rural area (TH 102.0 ± 18.3 D). Further analysis found the OLSDs for high lightning strokes for an OLSD (≥500) in the urban city areas (LH 6.3 ± 3.1 D, HG 7.0 ± 4.1 D) and the mountainous rural area (TH 5.0 ± 2.7 D), for medium lightning strokes for an OLSD (10–499) in all five observation areas (LH 47.3 ± 13.5 D, HG 42.3 ± 8.4 D, ZML 37.3 ± 9.6 D, JGW 56.3 ± 12.8 D, TH 41.3 ± 4.1 D), and for low lightning strokes for an OLSD (<10) in all five observation areas (LH 59.7 ± 6.0 D, HG 62.7 ± 13.8 D, ZML 63.3 ± 9.3 D, JGW 82.0 ± 10.5 D, TH 55.7 ± 18.0 D). The distribution of OLSDs with respect to lightning stroke frequency for an OLSD while thunderstorm traversing the observation areas over the study period is illustrated in Figure 3. Double peak feature is found for the urban city and town LH, HG, and ZML at 10–49 and 100–499 lightning stroke intervals for an OLSD. There was only one peak for the suburban JGW at 10–49 lightning stroke interval for an OLSD and no obvious peak for TH. The 2009 and 2010 patterns were quite close, but there was less variation for 2011 over the five microenvironmental observation areas. The indication is that lightning behavior is not only affected by the variation in the microenvironment but also affected by the variation in meteorological conditions for the respective years. Thus, the impact of weather on lightning activities needs further future study.

Although the OLSDs in JGW were the highest, the number of major thunderstorm days (MTSDs) was much less than those in other observation areas. A major thunderstorm (MTS) affecting an observation area is one with more than 100 lightning strokes continuously appeared in that area while the thunderstorm was traversing through. The highest number of MTSDs was found in LH (24.7 ± 9.1 D), followed by HG (20.3 ± 7.1 D), TH (16.0 ± 2.7 D), and ZML (15.0 ± 5.2 D), while JGW (14.7 ± 3.6 D) had the lowest MTSDs. Convective invigoration due to the structural high rise buildings in megacity Guangzhou, Dongguan city, and the mountainous barrier in the north of TH should be the main reason for the higher MTSDs found for LH, HG, and TH. The reason for lower MTSDs in ZML and JGW is that ZML is in a municipal town containing mainly low-elevation buildings and JGW is located in a suburban area less affected by urban induced convective motion.

Westcott [1995] found an enhancement of lightning frequency on the order of 40–85% over and downwind of major urban areas in midwestern U.S. with NLDN data. *Pinto et al.* [2004] studied the lightning activity over Belo Horizonte, southeastern Brazil, and nearby surrounding areas. The authors indicated a significant enhancement of approximately 100% in the −CG flash density and 50% in the +CG flash density over and downwind of the city, compared with the other adjacent areas. From Table 2, we found that for urban areas, the annual lightning stroke densities in megacity LH (39.5 ± 3.4 str km^{-2} yr^{-1}) and city HG (45.9 ± 15.4 str km^{-2} yr^{-1}) were 75–103% more than those in municipal town ZML (22.6 ± 11.4 str km^{-2} yr^{-1}). The annual lightning stroke density found in the mountainous rural area (TH 27.7 ± 8.8 str km^{-2} yr^{-1}) which had the lowest OLSDs was higher than that in the hilly suburban area (JGW 23.9 ± 10.8 str km^{-2} yr^{-1}) with the highest OLSDs. However, annual lightning stroke density in ZML was slightly lower than that in JGW. It contradicts

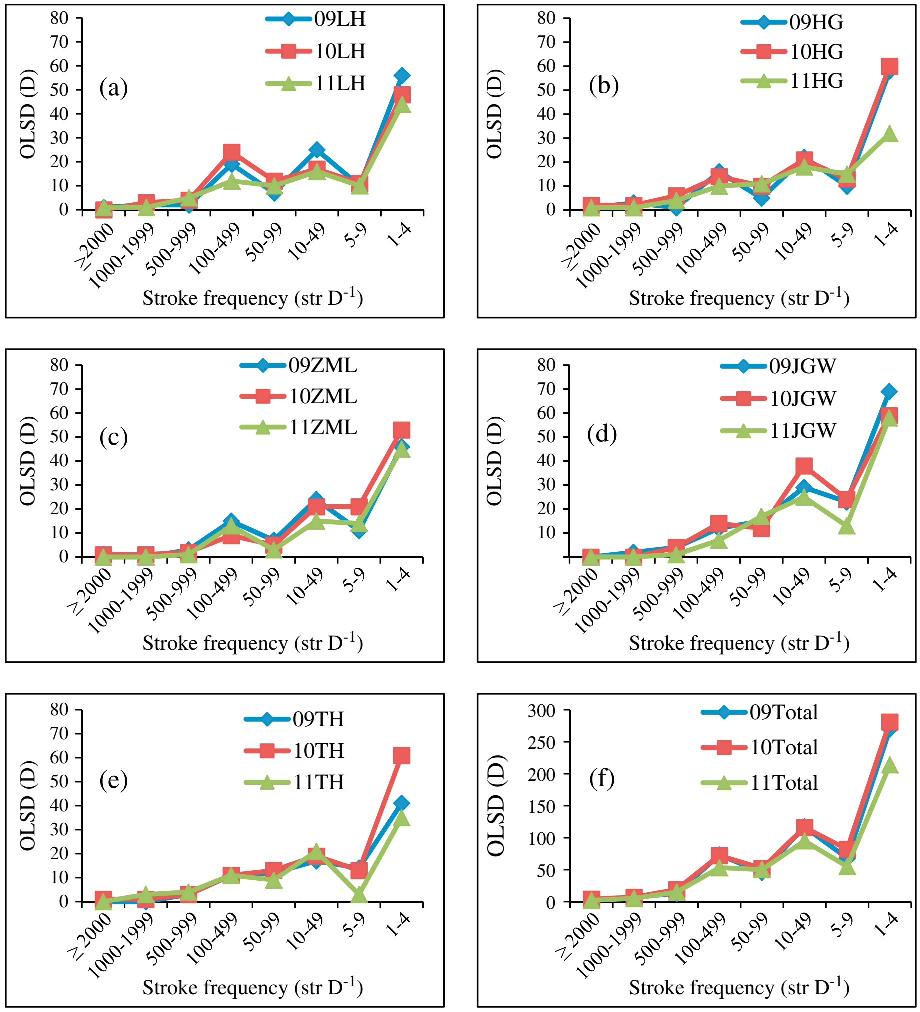

Figure 3. OLSD versus lightning stroke frequency per OLSD while thunderstorm traversing the five observation areas in PRD in 2009–2011: (a) LH, (b) HG, (c) ZML, (d) JGW, (e) TH, and (f) Total.

with the lightning behavior observation. Lightning strokes were found to be denser in municipal town ZML than in suburban JGW. The reason is that the total lightning strokes for all thunderstorms in ZML as well as in JGW during the observation period were used in the calculation. In fact the number of OLSDs in JGW was about 38% higher than that in ZML. Thus, although the total lightning strokes and annual lightning stroke density in JGW was calculated to be about 6.0% more, the calculated average lightning stroke density for an OLSD was about 23.2% less in JGW. It was mainly due to the fact that lightning strokes over the city areas were more in a single thunderstorm. Thus, it can be seen that annual averaging analysis technique can be misleading in describing lightning behavior. Hence, an observational approach can tell us more about the behavior of lightning activities in differing microenvironment. This phenomenon was also reflected in the higher lightning activities while the thunderstorm was traversing over ZML as compared to the low lightning activities over JGW as shown in the next section.

5.2.2. Observation-Based Investigation of Thunderstorm Path

To illustrate the relationship between lightning activities and the observable lightning strokes for an OLSD, respective MTSs in the five observation areas were examined. In contrast to the study of *Ashley et al.* [2012], and instead of using the high-resolution radar reflectivity, spatiotemporal histories of CG lightning activities over the five observation areas for 274 MTSs in 2009–2011 were plotted out and studied. In this paper, typical cases for the five observation areas are presented. The thunderstorm traversing path methodology was used. Thunderstorm activities in 2011 were used to illustrate the methodology, and relevant case studies

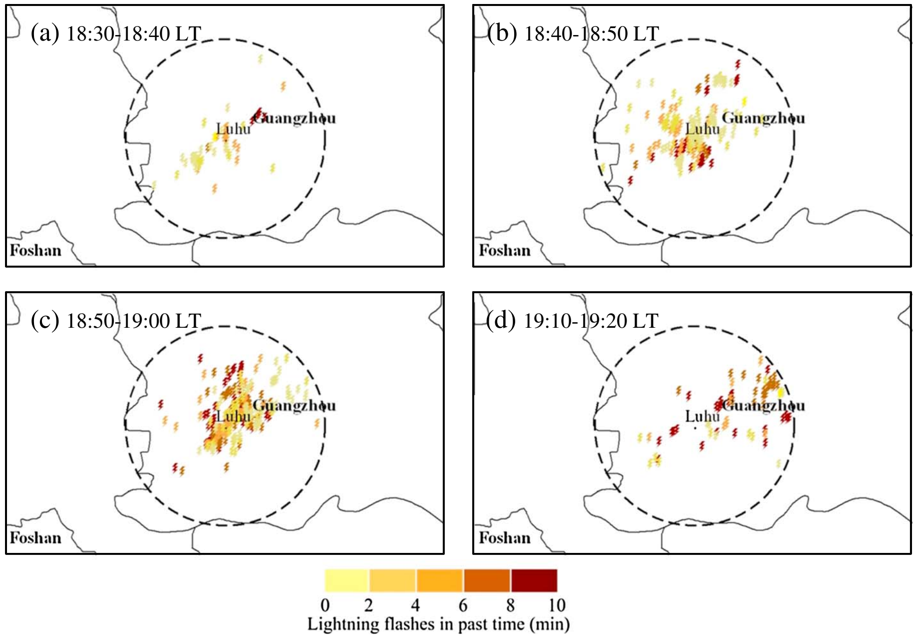

Figure 4. Thunderstorm path of CG lightning in LH from 18:30 to 19:20 LT on 17 July 2011: (a) lightning appearing 18:30–18:40, (b) lightning development 18:40–18:50, (c) lightning fully developed 18:50–19:00, and (d) lightning leaving 19:10–19:20. (Lightning positions are color coded in 2 min intervals and the thunderstorm approach path was southwest.)

are presented. Lightning activity of CG lightning in a thunderstorm case in LH from 18:30 to 19:20 local time (LT) on 17 July 2011 is shown in Figure 4. The thunderstorm first appeared at 18:30–18:40 LT (Figure 4a, 49 lightning strokes), developed at 18:40–18:50 LT (Figure 4b, 178 lightning strokes), fully developed at 18:50–19:00 LT (Figure 4c, 230 lightning strokes), and left at 19:10–19:20 LT (Figure 4d, 64 lightning strokes). It was clear that the direction of this thunderstorm approach was from the southwest. Similar to LH, typical thunderstorm paths of CG lightning in HG, ZML, JGW, and TH are presented in Figures 5–8, respectively. The

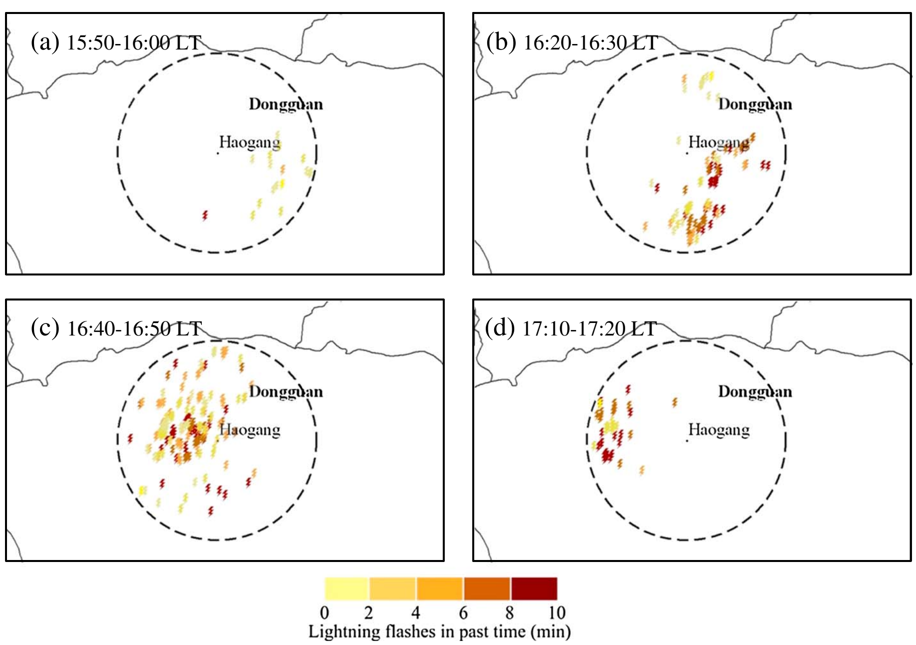

Figure 5. Thunderstorm path of CG lightning in HG from 15:30 to 17:30 LT on 27 July 2011: (a) lightning appearing 15:50–16:00, (b) lightning development 16:20–16:30, (c) lightning fully developed 16:40–16:50, and (d) lightning leaving 17:10–17:20. (Lightning positions are color coded in 2 min intervals and the thunderstorm approach path was southeast.)

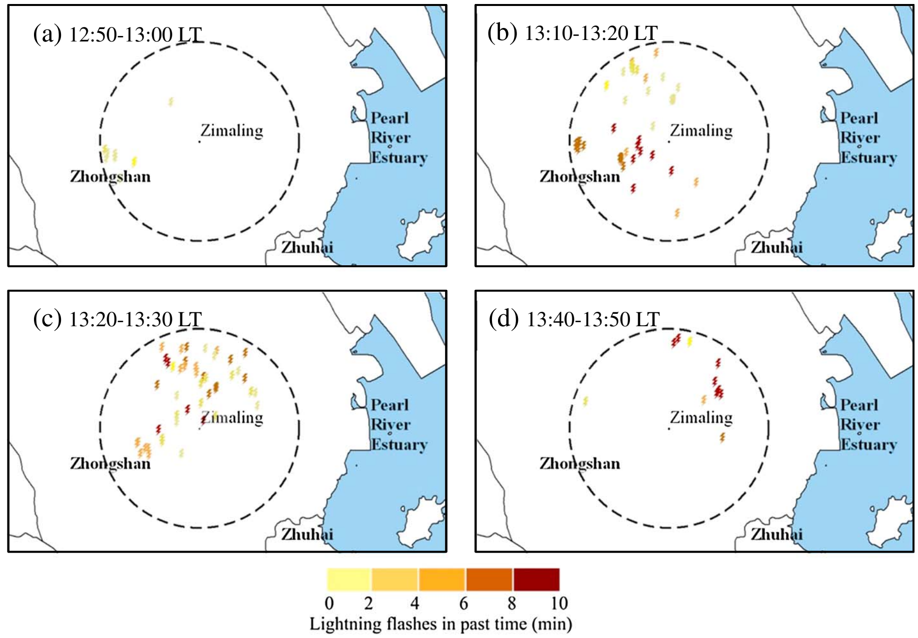

Figure 6. Thunderstorm path of CG lightning in ZML from 12:50 to 13:50 LT on 16 May 2011: (a) lightning appearing 12:50–13:00, (b) lightning quick development 13:10–13:20, (c) lightning fully developed 13:20–13:30, and (d) lightning leaving 13:40–13:50. (Lightning positions are color coded in 2 min intervals and the thunderstorm approach path was southwest.)

other typical cases in 2009 and 2010 are presented in Figures S1–S10 of SI. Dates, days within week, number of lightning stroke, and directions of the MTSs traversing the five observation areas are presented in Tables S1–S3 of SI. The southwest was the favored thunderstorm approach path for the five observation areas, and the southeast is also a favorable direction for major urban and urban areas. In our study, the southwest thunderstorm path was favored during May and June in the first rainy season period while the southeast was favored during July and August in the second rainy season period. Nevertheless, there was overlapping of these two directions in both rainy seasons.

In the following analysis, OLSDs with the fourth or fifth high lightning strokes in 2009–2011 were selected in all case studies for the urban city areas LH, HG, and ZML (Figures 4–6, S1–S3, and S6–S8). We found that lightning strokes occurred intensively when the thunder cloud moved above the megacity (LH) and city (HG) (Figures 4, 5, S1, S2, S6, and S7). The lightning strokes in LH and HG case were (20–170%) more than that in the municipal town (ZML) case. We also noted that the observable lightning stroke density for an OLSD during MTS period in hilly suburban JGW was 33–42% lower than that in ZML, and this is comparably more than that calculated previously for an OLSD (23.2%). In JGW, the corresponding CG lightning was highly dispersive over the thunderstorm traversing through period (Figures 7, S4, and S9).

5.2.3. Impact of Urban Effect and Topography

In urban area, because of the urban high buildings and urban heat island effect, convectional air mass uplift is strong. Moreover, increased level of air pollutants from anthropogenic sources carried by the uplifted air mass to the thunderstorm cloud helped the production of numerous small droplets and thereby suppressed mean droplet size. The latter effect would enable more cloud water to reach the mixed phase region where it is involved in the formation of precipitation and the separation of electric charge, leading to an enhancement of lightning [*Orville et al.*, 2001]. Also, elevated aerosol loading can result in enhanced concentration of cloud condensation nuclei, which have major impact on the cloud microphysical processes [*Ackerman et al.*, 2000], resulting in the enhancement of lightning activities.

The urban effect includes those due to the urban heat island and the urban aerosol. It is highly related to population, urban size, and urban structure. In this study, we followed the approach of *Westcott* [1995]. The change in OLSD and intensiveness of the lightning strokes over the observation areas were examined with regard to urban population, size, and structure described in section 3. The OLSDs of the megacity LH was

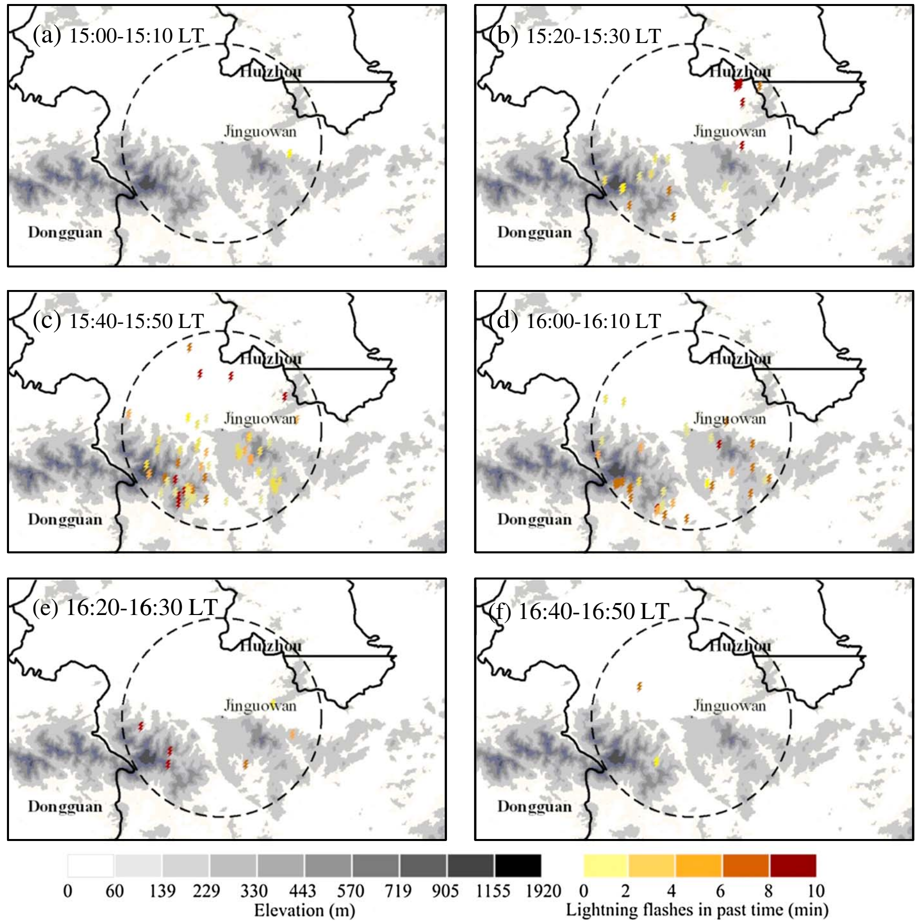

Figure 7. Thunderstorm path of CG lightning in JGW from 15:00 to 16:50 LT on 11 June 2011: (a) lightning appearing 15:00–15:10, (b) lightning development 15:20–15:30, (c and d) lightning fully developed 15:40–15:50 and 16:00–16:10, and (e and f) lightning leaving 16:20–16:30 and 16:40–16:50. (Lightning positions are color coded in 2 min intervals and the thunderstorm approach path was southwest.)

close to the OLSDs of the city HG. Nevertheless, the OLSDs of LH and HG were about 8.7–9.7% over the municipal town ZML. The indication is that enhancement of OLSD is related to the population, size, and structure in the urban area. Although the OLSDs in LH and HG were similar, we found that the annual observable lightning stroke density of HG was 16% higher than that of LH. HG is located in the industrial Dongguan city, which had high industrial particulate emission. Thus, we should add the industrial aerosol effect to the urban population, size, and structure effect in Dongguan, a main manufacturing center of China. The annual lightning stroke density of ZML was 6% less than JGW. However, in the previous section, we had demonstrated that lightning strokes in JGW were much more dispersive and less in frequency while the thunderstorms was traversing through (Figures 6 and 7). In Figure 8, we noted that the lightning strokes occurred most before the thunder cloud moved over the high-elevation mountains, which was different from those occurred in the megacity area LH where lightning activities developed and lightning densely stroke over the city (Figures 4b and 4c). When the thunder cloud approached the mountain barrier, the orographic uplift induced dense lightning strokes. However, the annual lightning stroke density was 9–40% smaller than those in LH and HG. It may due to the less convective uplift of thunderstorm for air masses approaching TH. It may also due to the subdue of weak thunderstorms caused by the loss of moisture and momentum after it traversed through the urban city and its downwind areas before it reached the mountain barriers surrounding TH in the north and northeast of the PRD region, and thus reducing the OLSDs.

Bornstein and LeRoy [1990] described how on days with calm regional flows New York City initiated convective activities and produced a radar echo frequency maximum over the city. Also, moving

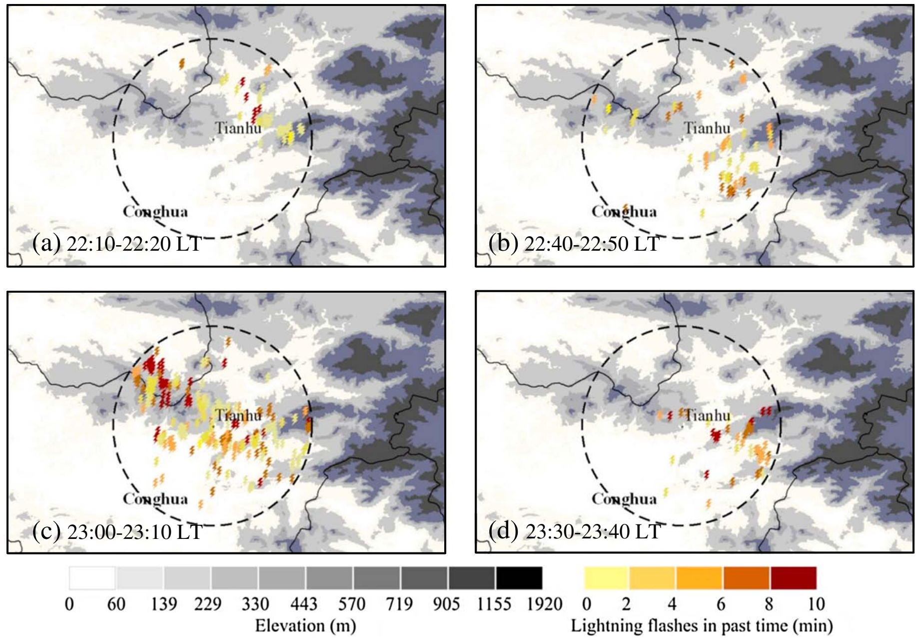

Figure 8. Thunderstorm path of CG lightning in TH from 22:00 to 23:40 LT on 25 June 2011: (a) lightning appearing 22:00–22:10, (b) lightning development 22:40–22:50, (c) lightning fully developed 23:00–23:10, and (d) lightning leaving 23:30–23:40. (Lightning positions are color coded in 2 min intervals and the thunderstorm approach path was southwest.)

thunderstorms were observed to bifurcate and move around New York City due to building barrier effects. It had also been suggested that future urban lightning studies should consider incorporating tall building data sets [*Burian et al.*, 2006] as proxies for the urban circulations induced by city morphology and surface roughness. Our observation-based investigation showed that the MTSs always climbed and passed over Guangzhou megacity producing dense lightning strokes over the city, illustrating that subtropical thunderstorms were usually much stronger than those occurred in midlatitude. Hence, quite different lightning characteristics, especially those related to building barrier effect, were found while thunderstorms traversed urban cities in different latitudes.

We give another illustration of the climate and urban effect. The lightning stroke number of the municipal town ZML (7088.0 ± 3581.5 str yr^{-1}) was larger than those over the nine small towns in central Spain (82–366 flashes for 3 years) reported by *Soriano and de Pablo* [2002]. This region is under the control of Mediterranean climate or temperate marine climate (in the northwest). PRD is characterized by the subtropical monsoon climate which produces much stronger thunderstorms. Also, ZML is quite different from the nine Spanish small towns. It is a bigger town and its neighborhood is highly urbanized. Hence, we found the great difference in the lightning stroke numbers. It demonstrates again that differences in the climatic and mircoenvironmental conditions can induce a great impact on lightning.

5.3. Temporal Variation of Lightning Stroke

After analyzing the −CG and +CG lightning diurnal variation (plots not shown here), we found that the patterns of −CG and +CG lightning diurnal variations in the five observation areas were similar. The diurnal variation of total CG lightning strokes for the five observation areas during the sampling period in 2009–2011 is presented in Figure 9. In the PRD region, most CG lightning happened between 13:00 and 19:00 LT in the afternoon and early evening (Figure 9f), when the atmosphere was generally the most unstable and convective development was more probable. This phenomenon suggested that lightning activities observed in the PRD region was related to the solar heating cycle, and consequently, the thunderstorm occurred mainly in the afternoon when land was heated up. There is hourly fluctuation in lightning stroke frequencies within this peak period. We observe lightning stroke frequency to be higher at 15:00, 17:00, and 18:00 LT for LH (Figure 9a), at 16:00 and 18:00 LT for HG (Figure 9b), and at 16:00 LT for ZML (Figure 9c) among the five microenvironments. It is more like a normal distribution for JGW (Figure 9d) and TH (Figure 9e).

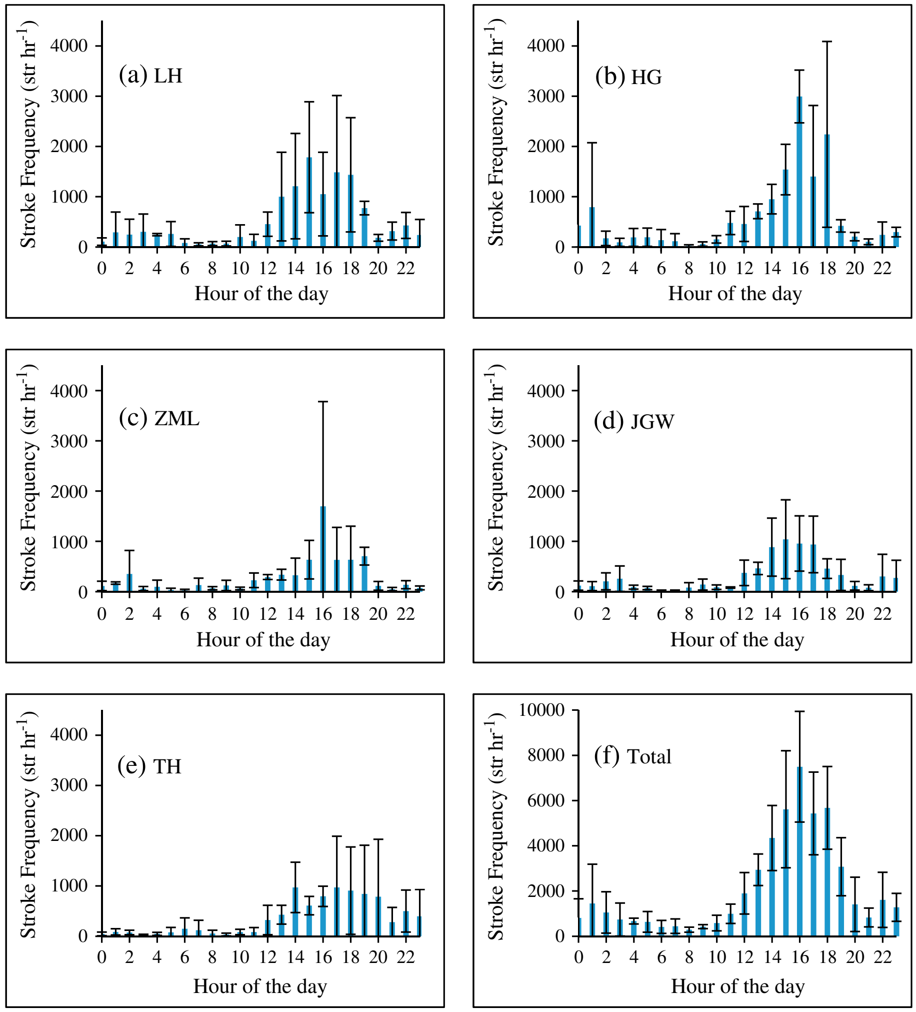

Figure 9. Diurnal variation of lightning strokes for the five observation areas during the sampling period in 2009–2011: (a) LH, (b) HG, (c) ZML, (d) JGW, (e) TH, and (f) Total. The blue histogram bar is the stroke frequency per hour per year. The black line segment represents the error bar of the stroke frequency. The hour of the day is local time.

We have investigated the variation of MTSDs on weekday and weekend during 2009–2011. We do not observe a particular pattern of distribution of MTSDs for the five observation areas among weekday and weekend even for the major city LH and city HG (Figure 10), which is different from the findings of *Bell et al.* [2009] who reported finding greater lightning activities over the eastern continental U.S. during the weekday than on weekend. The implication may be that the climatic and weather effect surpasses the weekday and

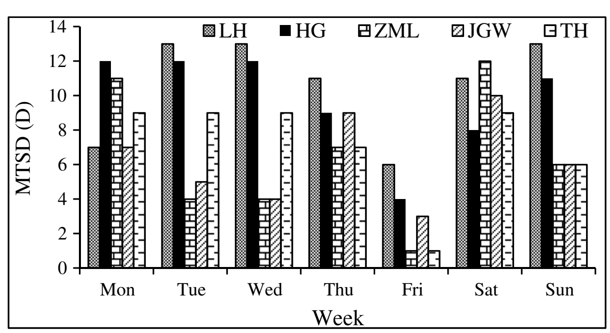

Figure 10. MTSD for the five observation areas in weekday and weekend during the sampling period in 2009–2011.

weekend effect or we do not have a long-term data set, such as over 10 years, to perform a pattern analysis. As an illustration, from our 3 years lightning data analysis of weekly variation, it seems that there is a pattern of decreased MTSDs between Tuesday and Friday over ZML and JGW and increased MTSDs on Saturday, Sunday, and Monday. However, we found that the MTSDs on Thursday were higher than those on Tuesday, Wednesday, Friday, and Sunday. This is due to the high frequency of thunderstorm days occurring on Thursday in 2010 (Tables S1–S3). Hence, it casts doubt on this weekday and weekend observation. MTSDs may be affected by the meteorological condition of particular years, and hence, we need more than 3 years to see if there is a reliable weekday-weekend pattern.

6. Conclusion

The high frequency of lightning activities in the PRD region and the existence of special features in relief, topography, population, urban size and structure, and thunderstorm strength provide a favorable platform for the application of a microenvironment- and observation-based analysis approach to study lightning activities in this region. Physical and observational lightning characteristic parameters for the five observation areas covering megacity, city, municipal town, hilly suburban area, and mountainous rural area were deduced from data recorded by the LLS for the period April to September 2009–2011 and examined. Our analysis showed that there were high variation of lightning characteristics and phenomenal changes among these areas. We noted that after upgraded twice since it came into operation in 1997, the performance of the South China Power Grid LLS had about 90% flash detection efficiency and less than 800 m location error in PRD during our study period. An observation-based thunderstorm traversing observation area methodology was developed. Special features and phenomenal changes observed while the thunderstorms were traversing over the five observation areas were found to have good correlation with the change of lightning characteristic parameters, in particular OLSDs, and observable lightning stroke frequency and density for an OLSD. Microenvironmental variation due to change in topography, degree of urbanization, urban effect, and thunderstorm strength was found to affect the spatial distribution of lightning stroke and the severity of lightning activities over these microenvironmental areas. Our approach increases the understanding of lightning activity as well as gives us a better picture of lightning behavior in the PRD region. We believe it will also be useful for future studies in other regions. Features as well as findings obtained in this study will be used to explore further whether we can generate a new approach for future study of LLS data and for exploring the lightning climatology in South China. Also, by comparing and contrasting our study with previous studies, we have demonstrated that climate and microenvironment are both important factors affecting lightning activity and behavior not only in the PRD region but also among different countries in different latitudes.

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