Climatological Comparison of Small- and Large-Current Cloud-to-Ground Lightning Flashes over Southern China

DONG ZHENG, YIJUN ZHANG, AND QING MENG
State Key Laboratory of Severe Weather, and Laboratory of Lightning Physics and Protection Engineering, Chinese Academy of Meteorological Sciences, Beijing, China

LIUWEN CHEN
Lightning Protection Center of Guangdong Province, Guangzhou, China

JIANRU DAN
Conghua Meteorological Bureau, Guangzhou, China

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ABSTRACT
The first climatological comparison of small-current cloud-to-ground (SCCG; peak current \( \leq 50 \text{kA} \)) and large-current cloud-to-ground (LCCG; peak current \( >50 \text{kA} \), \( >75 \text{kA} \), and \( \geq 100 \text{kA} \)) lightning flashes is presented for southern China. The LCCG lightning exhibits an apparent preference to occur over the sea. The percentage of positive LCCG lightning during the nonrainy season was more than twice that during the rainy season, while the percentage of positive SCCG lightning showed small seasonal differences. Positive cloud-to-ground (PCG) lightning was more likely to feature a large peak current than was negative cloud-to-ground (NCG) lightning, especially during the nonrainy season and over land. Distinct geographical differences are found between SCCG and LCCG lightning densities and between their own positive and negative discharges. Furthermore, the percentages of positive lightning from LCCG and SCCG lightning exhibit distinctly different geographical and seasonal (rain and nonrainy season) distributions. The diurnal variations in SCCG and LCCG lightning are clearly different over the sea but similar over land. Diurnal variations in the percentage of positive lightning are functions of the peak current and underlying Earth’s surface. In combination with the University of Utah precipitation feature (PF) dataset, it is revealed that thunderstorms with relatively weak convection and large precipitation areas are more likely to produce the LCCG lightning, and the positive LCCG lightning is well correlated with mesoscale convective systems in the spatial distribution during nonrainy season.

1. Introduction
The climatology of lightning flashes, which can act as an effective indicator of deep convection and climate change, has been widely studied around the world (e.g., Hidayat and Ishii 1998; Orville and Huffines 2001; Soriano et al. 2001; Orville et al. 2002; Altaratz et al. 2003; Christian et al. 2003; Qie et al. 2003; Kandalgaonkar et al. 2005; Ma et al. 2005; Kuleshov et al. 2006; Mazarakis et al. 2008; Rudlosky and Fuelberg 2010; Chronis 2012; Chronis et al. 2015; Yang et al. 2015). These studies have investigated the geographical distribution and seasonal and diurnal variability of lightning discharge parameters (e.g., frequency, percentages of different-polarity lightning, peak current, and multiplicity) generally using lightning data as a whole. Thus, the question remains whether cloud-to-ground (CG) lightning flashes with different peak-current magnitudes have different climatological characteristics.

Special attention has been paid to large-current CG (LCCG) lightning in several previous studies (e.g., Lyons et al. 1998; Kochtubajda et al. 2006; Pinto et al. 2009). In these studies, LCCG lightning is usually defined as having a peak current higher than 75 kA (e.g., Lyons et al. 1998; Pinto et al. 2009) or 100 kA (e.g., Kochtubajda et al. 2006). These studies have revealed distinct geographical differences in the spatial distribution of positive and
negative LCCG lightning. Furthermore, it was also reported by Pinto et al. (2009) that the density distributions for negative and positive LCCG lightning differed from the lightning density distributions for all negative and positive cloud-to-ground (NCG and PCG, respectively) lightning. It has been proposed that a positive LCCG lightning density distribution and the distribution of the percentage of positive LCCG lightning were related to the occurrence of mesoscale convective systems (MCSs) (e.g., Lyons et al. 1998; Pinto et al. 2009).

Furthermore, it was reported that PCG lightning accounts for a relatively higher proportion of LCCG lightning than for total CG lightning. For example, while the percentage of PCG lightning from CG lightning was around 5% during summer months within the continental United States (cf. Fig. 12 in Orville and Huffines 2001), Lyons et al. (1998) used U.S. National Lightning Detection Network (NLDN) data from 14 summer months to show that, for peak current >75 kA and >200 kA, the percentages of their positive parts were 13.5% and 19.6%, respectively. Based on data from the Canadian Lightning Detection Network (CLDN) during 1999–2004, Kochtubajda et al. (2006) showed that approximately 51% of the LCCG lightning was positive compared with 17.5% of all CG lightning. In addition, Pinto et al. (2009) found that a PCG lightning flash was 3.1 times more likely to exceed 75 kA than was a NCG lightning flash across the continental United States.

Other studies have found that the peak current in CG lightning depends on surface conditions and local time, but did not examine the characteristics of CG lightning classified by peak-current magnitudes. The difference between peak current in CG lightning over land and ocean has been reported in some studies (e.g., Biswas and Hobbs 1990; Orville and Huffines 2001; Seity et al. 2001; Steiger and Orville 2003; Rudlosky and Fueleberg 2010; Orville et al. 2011; Chronis 2012; Hutchins et al. 2013; Said et al. 2013). These show greater peak current over the ocean and sharp increases along coastlines, especially for the NCG lightning. Furthermore, Chronis et al. (2015) concluded that the peak current in NCG lightning increases from late evening to early morning and decreases during the afternoon. This is the inverse of diurnal patterns observed for CG lightning activity.

The climatological characteristics of lightning activity across China have been studied by Ma et al. (2005) using flash data from the satellite-borne Optical Transient Detector and Lightning Imaging Sensor (LIS), and by Yang et al. (2015) using CG lightning data from the China Lightning Detection Network. These studies show an increase in lightning density from west to east and north to south in China, with the strongest lightning activity occurring in southern China. Using LIS flash data over southern China, Wang et al. (2009) concluded that the lightning flash number during April–August accounted for 81.91% of the annual total, and that the main lightning activity peak occurred between afternoon and early evening. Based on a regional CG lightning location network, Zhang et al. (2000) analyzed lightning activity in Guangdong Province of southern China. They found that PCG lightning accounted for 5.03% of the total, with high-density lightning activity located near Guangzhou.

In this paper, we focus on the climatological differences between SCCG and LCCG lightning by analyzing CG lightning data in southern China, mainly in Guangdong Province and its adjacent sea. We further compare SCCG and LCCG lightning across seasons (rainy and nonrainy seasons) and underlying Earth’s surface (land and offshore water), and discuss the association of LCCG lightning with the intensity of thunderstorms and the association of positive LCCG lightning with MCSs.

2. Observations and data

2.a. Study area

The study region (Fig. 1) has a total area of approximately 244 000 km², including the land within Guangdong Province in southern China (approximately 180 000 km²), and an adjacent stretch of the South China Sea (64 000 km²). The seaward extent of the study region was limited to approximately 100 km from the coastline to ensure reliable detection by the lightning location system.

The study region has a subtropical monsoon climate with two rainy seasons (Ding and Wang 2008). The first rainy season generally occurs from April to June when the well-known summer monsoon prevails (e.g., Xu et al. 2009; Zheng and Cheng 2011; Luo et al. 2013; Xu 2013). The MCSs are the dominant rainfall producers, contributing about 90% of the total near-surface rainfall (Luo et al. 2013). The second rainy season generally occurs from July to September during which large-scale precipitation is usually produced by tropical cyclones or other tropical weather systems. In a preliminary analysis of this study, we found that there were only small differences between the characteristics of CG lightning activity during the first rainy season and during the second rainy season. Therefore, the lighting activities during these two rainy seasons were studied as a whole. We use the term “rainy season” to denote these two rainy seasons and “nonrainy season” for other months. The study region features the highest lightning activity in China, based on global (e.g., Christian et al. 2003) or Chinese (e.g., Ma et al. 2005; Yang et al. 2015) lightning...
distribution maps. Furthermore, Guangdong Province is reported to have the most lightning-related casualties and damage in China (Zhang et al. 2011).

b. Observational data and processing

1) LIGHTNING LOCATION SYSTEM

CG lightning data are collected by the Guangdong Lightning Location System (GDLLS), operated by the State Grid Electric Power Research Institute. This system began operation in 1996 and, by 2000, comprised a network of 16 time-of-arrival/magnetic direction finder sensors (Fig. 1). From 2007 to 2010, the system was further upgraded and the number of sensors increased to 27 (Fig. 1). GDLLS data from 2001 to 2013 are used for this study.

Using data for transmission line faults caused by lightning, Chen et al. (2002) showed that the overall GDLLS CG lightning detection efficiency and median error of the location accuracy were approximately 86% and 1.3 km, respectively, in 1999 when there were (temporarily) 14 sensors in the network. Chen et al. (2012) evaluated the performance of the GDLLS in Guangdong Province based on observations of triggered lightning in Conghua during the period 2007–11, and of natural lightning striking tall structures in Guangzhou between 2009 and 2011. Their results show that the CG lightning detection efficiency and stroke detection efficiency were about 94% and 60%, respectively, and the median values for location error were approximately 489 m. The absolute percentage errors of peak-current estimation were reported to be within the range of 0.4%–42%, with a median value of about 19.1%. It is clear that during and after the upgrade from 2007 to 2010, the performance of GDLLS experienced moderate improvement. In contrast, Nag et al. (2011) used triggered lightning data during 2004–09 to show that the lightning and stroke detection efficiencies from the U.S. NLDN were 92% and 70%, respectively, and the median current estimation error was 13%.

2) LIGHTNING DATA PROCESSING

Original return stroke (RS) data were grouped using the criterion that adjacently located RSs for one lightning flash should occur within an interval of 0.5 s and at a distance of 10 km. Each RS involved in one flash was investigated to get the number of sensors participating in its location. Furthermore, the maximum peak current among the RSs was taken to be the lightning current. Following previous studies (e.g., Cummins et al. 1998), PCG lightning with current less than 10 kA was removed from the dataset because it could be a misinterpretation of cloud lightning. CG lightning flashes were divided into two categories: lightning with a
peak current no larger than 50 kA was defined as SCCG lightning, and that with a peak current above 50 kA was defined as LCCG lightning. The latter category was further split into three types: CG lightning with peak current above 50, 75, and 100 kA, hereafter referred to as CG_{50}, CG_{75}, and CG_{100} lightning, respectively. These categories were adopted with the aim of investigating the change in LCCG lightning characteristics with the increase in the peak-current threshold. However, we focus on CG_{75} lightning, as this was the definition of LCCG lightning used in previous studies (Lyons et al. 1998; Pinto et al. 2009).

A total of more than 23 \times 10^6 CG lightning flashes were detected within the analysis region between 2001 and 2013. The percentages of CG lightning that occurred during rainy and nonrainy seasons were 95.6% and 4.4%, respectively. In addition, 83.9% of CG lightning flashes were recorded over land and 16.1% over sea. In the analysis on the geographic distribution of the lightning features, the values were counted in 0.5° latitude–longitude resolution grids, and then plotted in 0.01° resolution grids by using a bilinear interpolation algorithm with the aim of avoiding the mosaic effect.

3) STABILITY OF LIGHTNING DATA

Because we focus on comparing the spatial distribution and diurnal variation of SCCG and LCCG lightning, the interannual variation of CG lightning data (probably caused by the interannual variation of convection activity or the performance of GDLLS) has a relatively weak effect on the analysis. However, the analysis might be sensitive to whether the performance of the GDLLS is uniform within the region and whether the nature of the data changed steadily during the different periods (before, during, and after the GDLLS upgrade).

We roughly examine the spatial variation in the detection efficiency of GDLLS in the analysis region by comparing the geographical distribution of the total lightning observed by LIS aboard the Tropical Rainfall Measuring Mission (TRMM) satellite (Kummerow et al. 1998) and CG lightning observed by GDLLS. High-resolution full-climatology (HRFC) TRMM LIS data (Cecil et al. 2014) with a grid size of 0.5° latitude–longitude were downloaded from the Global Hydrology Resource Center (GHRC) website (http://thunder.msfc.nasa.gov/data/data_lis-otd-climatology.html). The detection efficiency of LIS varies with time of day. Following Boccioppio et al. (2002), it changed between about 73% ± 11% for noon and 93% ± 4% for night. Here, we make an assumption that the geographical patterns of the total lightning (TRMM LIS) and CG lightning (GDLLS) densities should be analogous in the study region.

Figure 2 shows the geographical distributions of LIS total lightning and GDLLS CG lightning. The spatial variations in lightning densities are highly congruous, including the highest-density areas, relatively strong lightning activity over land, weak lightning activity over sea, and the sharp transition along the interface between land and sea. Note that a detailed analysis of the geographical distribution of CG lightning is included in section 3b. According to the central positions of the grids over land or over sea, we further calculated the ratio of GDLLS CG lightning to LIS total lightning over land and over sea, both in 0.5° latitude–longitude grids, and obtained approximate values of 0.43 and 0.46, respectively. The similar patterns of GDLLS CG and TRMM LIS total lightning densities over land and sea should suggest that the detection efficiency of GDLLS in the study region should be within a reliable range.

The average number of sensors involved in the location and the minimum absolute peak current of negative RSs are further investigated in 0.5° latitude–longitude grids and exhibited in Fig. 3. The upgrade to the GDLLS increased the number of sensors involved in the location of RSs across the whole study region, which would have contributed positively to location accuracy. Meanwhile, there was no distinct land–sea difference in the number of sensors involved in the location, while more sensors participated in the location in the center area of the study region. The minimum detected absolute peak current of negative RSs changed little during the different periods, while their values were kept small (the values were impacted by not only the performance of GDLLS but also the features of the samples during different periods and over discrepant surfaces). Generally speaking, the GDLLS’s detection performance in the chosen region can support this study.

4) AUXILIARY DATASET

Besides the primary CG lightning data, the University of Utah TRMM-based precipitation feature (PF) dataset from 2001 to 2013 is used in section 4 to characterize the structure and convective properties of precipitation systems (available at http://trmm.chpc.utah.edu/). The PF dataset (Liu 2007; Liu et al. 2008) was developed by collecting multiple observations from four different instruments aboard the TRMM satellite: Precipitation Radar (PR), TRMM Microwave Imager (TMI), Visible and Infrared Scanner (VIRS), and LIS. A PF is defined as a contiguous area consisting of TRMM 2A25 data near-surface raining pixels.

3. Analysis and results

a. Overview of the CG lightning flashes

Some basic characteristics of CG lightning data are shown in Fig. 4. In the following analysis, quantitative
land–sea and seasonal contrasts are described based on the lightning location data; that is, a CG lightning flash is defined as a land flash or a sea flash based only on its location over land or sea.

Figure 4a shows the percentages of the different CG lightning types (SCCG or LCCG lightning under different peak-current thresholds) in total CG lightning. This shows that the percentage of CG75 lightning (5.8%) is slightly greater than the amount reported by Lyons et al. (1998) (2.4%) and that reported by Pinto et al. (2009) (3%). The percentage of CG100 lightning (2.9%) is also greater than reported by Kochtubajda et al. (2006) (0.6%).

According to Fig. 4a, LCCG lightning was proportionately slightly more frequent during the rainy season than during the nonrainy season. In contrast, the land–sea differences were very distinct. While the SCCG lightning was more common over land than sea, LCCG lightning was much more likely to occur over sea. The finding that CG lightning tends to have a larger peak current over ocean than land agrees with results from other studies (e.g., Biswas and Hobbs 1990; Orville and Huffines 2001; Seity et al. 2001; Steiger and Orville 2003; Rudlosky and Fuelberg 2010; Orville et al. 2011; Chronis 2012; Hutchins et al. 2013; Said et al. 2013). In addition, the land–offshore contrast in the percentage of LCCG
lightning extends with the increase of the LCCG lightning peak-current threshold.

Next, we considered the percentages of PCG lightning from different CG lightning types (Fig. 4b). The percentage of positive lightning was higher for LCCG lightning than SCCG lightning, which is consistent with results from other studies (Lyons et al. 1998; Kochtubajda et al. 2006; Pinto et al. 2009). Furthermore, the percentage of positive LCCG lightning increased with increasing peak-current threshold. Positive CG$_{75}$ lightning was 12.3%, which is close to the 13.7% reported by Lyons et al. (1998) but less than the 21% reported by Pinto et al. (2009). Positive CG$_{100}$ lightning was 13.7%, and significantly less than the 51% reported by Kochtubajda et al. (2006).

The percentage of positive SCCG lightning shows slight differences related to both the season and underlying Earth’s surface. However, the percentage of positive LCCG lightning during the nonrainy season was more than twice that during the rainy season. Some studies have demonstrated that a larger percentage of PCG lightning occurs during cold seasons than warm seasons (e.g., Orville and Huffines 1999; Pinto et al. 2006; Yang et al. 2015). According to Jian (1994), in southern China, spring corresponds to April, summer is from May to September, autumn corresponds to October, and winter is from November to March. Therefore, the nonrainy season is approximately parallel to the cold season in the study region. The results of this study suggest that the most distinct difference in positive lightning ratio between cold (nonrainy) and warm (rainy) seasons occurs in LCCG lightning. The land–sea contrast in the percentage of positive LCCG lightning is not as prominent as the seasonal contrast; however, the percentages were smaller over land than over sea for SCCG and CG$_{50}$ lightning. This situation was reversed for CG$_{75}$ and CG$_{100}$ lightning.

We also considered the percentage of different CG lightning types that occurred in PCG ($P_{PCG}$) and NCG ($P_{NCG}$) lightning. The ratios of $P_{PCG}$ to $P_{NCG}$ are investigated and shown in Fig. 4c to explore the differences in PCG or NCG lightning contributing to different CG lightning types. It is apparent that the percentages of LCCG lightning from PCG lightning were larger than in
NCG lightning, and furthermore, this tendency increased with an increase in the peak-current threshold. For example, a PCG lightning flash was 1.5 times more likely than an NCG lightning flash to exceed 75 kA, which is lower than the likelihood of 3.1 times reported by Lyons et al. (1998). In addition, the difference in the percentages of LCCG lightning from PCG and NCG lightning was more prominent during the nonrainy than the rainy season, and was greater over land than over sea, while the LCCG lightning from PCG lightning maintains a larger percentage than that from NCG lightning.

**b. Geographical distribution of lightning density**

In this section, we focus on geographical differences in the distribution of SCCG and LCCG lightning during the rainy and nonrainy seasons. Figures 5a and 5b reveal that, during the rainy season, positive and negative SCCG lightning flashes both exhibit the highest densities in a region over the Pearl River delta (PRD) centered on Guangzhou and the secondary high-density regions to the north of the Leizhou Peninsula (LP). The density along the coastline decreased sharply from land toward sea.

Interestingly, the distributions of positive and negative SCCG lightning varied during the nonrainy season (Figs. 5c, d) and were entirely different from the patterns of their counterparts during the rainy season. Compared to that, the highest densities of both positive and negative lightning were located over PRD during the rainy season (Figs. 5a, b); during the nonrainy season, the highest density of positive SCCG lightning generally occurred along the central coastline in the study region (Fig. 5c), and that of negative SCCG lightning was distributed across the midwestern part of the study region (Fig. 5d). In addition, the gradient of SCCG lightning densities along the coastline during the nonrainy season was not as steep as during the rainy season.

Figure 6 shows the density distributions of positive and negative CG75 lightning during the two seasons. The spatial distributions of the CG50 and CG100 lightning were qualitatively similar, and are therefore not shown. The distributions of LCCG and SCCG
lightning showed geographical differences during the two seasons. During the rainy season, the positive and negative LCCG lightning both had their high-density centers over the PRD (Figs. 6a,b); however, their locations were more inclined to the mouth of the Pearl River, compared to those of the positive and negative SCCG lightning during the same season. The positive LCCG lightning had another high-density center to the north of LP, whereas the negative LCCG lightning density was not prominent.

During the nonrainy season, the highest density of positive LCCG lightning was mainly found over mountainous areas to the north of the analysis region (Fig. 6c). The highest density of negative LCCG lightning, however, occurred in the west of the PRD, with some large densities scattering in some other isolated centers (Fig. 6d).

The above analysis indicates that the distribution of CG lightning was peak-current dependent, which agrees with the observations of Lyons et al. (1998), Kochtubajda et al. (2006), and Pinto et al. (2009). Furthermore, the distribution of CG lightning was also seasonally dependent. According to Figs. 2, 5, and 6, the PRD experiences the most active lightning activity, especially during the rainy season and for SCCG lightning.

The most vigorous lightning activity over PRD might be related to several factors. The first factor might be associated with the trumpet-shaped terrain of PRD (see Fig. 1), which is half-surrounded by mountains and opens toward the ocean. In studies of convection and rainfall characteristics over southern China, Xu et al. (2009) and Luo et al. (2013) suggested that the mountains could lift the flow carrying abundant moisture from the ocean, which provided forced ascent and moisture for new convection or precipitation enhancement. The second factor might be attributed to the urban heat island effect and the roughness associated with PRD urban agglomerations. Based on the numerical simulation studies, Meng et al. (2007, 2012, 2014) reported that the urban heat island and the urban roughness over PRD both positively contributed to the enhancement of convergence around the urban areas. The third factor might be the relatively higher aerosol content.
et al. (2011) reported a larger annual mean aerosol optical depth over PRD relative to the surrounding area (see their Fig. 1). They suggested that aerosols in the PRD region supported more efficient mixed-phase processes and intense convection (Williams and Stanfill 2002; Williams et al. 2002, 2004; Kumar and Kamra 2010), and thus they might play an important role in enhancing lightning activity.

c. Geographical distribution of ratios of LCCG lightning from total CG lightning

The geographical distribution of the ratio of CG75 lightning to total CG lightning is shown in Fig. 7 (the geographical distributions of the CG50 and CG100 lightning ratios are not shown but are analogous to Fig. 7). During the rainy season, there was a clear preference for LCCG lightning to occur over sea (Fig. 7a), which agrees with other studies that have documented a larger median or mean peak current over sea than over land (e.g., Orville and Huffines 2001; Orville et al. 2011; Chronis 2012; Hutchins et al. 2013; Said et al. 2013). During the nonrainy season, however, the higher frequency of LCCG lightning over sea was not as distinct as during the rainy season (Fig. 7b).

d. Geographical distribution of ratios of positive lightning from SCCG and LCCG lightning

Figure 8 shows the geographical distributions of PCG lightning ratios in different CG lightning types during the rainy and nonrainy seasons. According to Figs. 8a,b, the ratios of positive SCCG lightning to total SCCG lightning during the rainy and nonrainy seasons have analogous spatial patterns, with greater values near the mouth of the Pearl River that extend to the eastern part of study region. But during the rainy season, the positive SCCG lightning ratios are distributed more continuously in space, and during the nonrainy season, the largest positive SCCG lightning ratios were located in the eastern part of the study region. The ratios of positive LCCG lightning (Figs. 8c,d), however, showed different spatial distributions to the ratios of positive SCCG lightning during all seasons. Furthermore, the ratio of positive LCCG lightning had different spatial patterns during different seasons. During the rainy season (Fig. 8c), areas with large positive LCCG lightning ratios were mainly located to the north of LP, while the PRD featured small values. During the nonrainy season (Fig. 8d), larger positive LCCG lightning ratios were distributed in the northern and northeastern parts of the analysis region.

e. Diurnal variation

Figure 9 shows diurnal variations in CG lightning activity based on all data during both the rainy and nonrainy seasons. We use CG75 lightning data to represent LCCG lightning. Diurnal variations in the CG50 and CG100 lightning are similar to those for CG75 lightning and are not shown.

Diurnal variations in the SCCG and LCCG lightning (Fig. 9a) exhibit a clear dependence on the underlying Earth’s surface. Both SCCG and LCCG lightning flashes over land reached their peak at 1600 local time (LT; indicating the period 1600–1700 LT), and a minimum at 0900 and 1000 LT, respectively. SCCG and LCCG lightning flashes over sea both had two peaks. For the SCCG lightning, the main peak occurred at 1700 LT and the second peak occurred at 0500 LT. In contrast, CG75 lightning had a main peak at 0700 LT and a second peak at 1800 LT. The CG50 and CG100 lightning flashes also had main peaks in the morning and secondary peaks in the afternoon.

The diurnal variation of lightning over land exhibits a close link to solar heating, which is consistent with the
variation of lightning over land described in other studies (e.g., Orville and Huffines 2001; Zipser et al. 2006; Holle 2014; Chronis et al. 2015). On the other hand, strong lightning activity during the late afternoon and early morning over sea were also reported for other global or regional ocean studies (e.g., Orville and Huffines 2001; Yang and Smith 2006; Holle 2014). As an exception, Chronis (2012) found that lightning activity did not have a clear diurnal preference for open water around Greece. In addition, Zheng and Cheng (2011) and Wu et al. (2013) exhibited the approximately analogous diurnal variation in convection activities over land and over sea in the analysis region.

Furthermore, we calculated that the main-peak densities of LCCG lightning are 1.1, 1.3, and 1.5 times the second-peak densities for the CG50, CG75, and CG100 lightning, respectively, which suggests that the main morning LCCG lightning peak changed more noticeably with an increase in peak-current threshold. Note that, from 2100 to 1100 LT, the LCCG lightning density over sea was even higher than over land. Meanwhile, the SCCG lightning from 2100 to 1100 LT was of similar density over land and sea.

Figure 9b shows the diurnal variation in the percentages of SCCG and LCCG lightning compared to the total CG lightning. SCCG lightning occurred more frequently in the afternoon, with peaks at 1600 LT over both land and sea; the percentage of CG75 lightning over land was highest at 0000 LT, while the percentage of CG75 lightning over sea peaked at 0800 LT. It is apparent that diurnal variations in the percentage of LCCG lightning have an inverse relationship with solar heating. This result is consistent with the findings of Chronis et al. (2015), who determined that the local peak current for NCG lightning increased in magnitude from late evening to early morning and decreased during the afternoon.

In terms of the percentages of positive lightning from different CG lightning types (Fig. 9c), the percentage of positive SCCG lightning types (Fig. 9c), the percentage of positive SCCG lightning compared to the total CG lightning. SCCG lightning occurred more frequently in the afternoon, with peaks at 1600 LT over both land and sea; the percentage of CG75 lightning over land was highest at 0000 LT, while the percentage of CG75 lightning over sea peaked at 0800 LT. It is apparent that diurnal variations in the percentage of LCCG lightning have an inverse relationship with solar heating. This result is consistent with the findings of Chronis et al. (2015), who determined that the local peak current for NCG lightning increased in magnitude from late evening to early morning and decreased during the afternoon.

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Fig. 9. Diurnal variations over land and sea in (a) the density of different CG lightning types (flashes km\(^{-2}\) day\(^{-1}\)), (b) the percentages of different CG lightning types from the total CG lightning, and (c) the percentages of the positive lightning from different CG lightning types.
depended on the underlying Earth's surface. The percentage of positive CG75 lightning over land peaked at 0900 LT (18.5%), and was lowest at 1600 LT (10.5%). The percentage of positive CG75 lightning over sea, however, peaked at 1400 LT (15.4%), and reached a minimum of 9.5% at 0000 LT. The percentages of positive CG50 and CG100 lightning were similar, except for a negligible difference in the times of the maxima and minima. The ratios of the highest to lowest percentages for CG50, CG75, and CG100 lightning were 2.1, 1.8, and 1.5, respectively, over land, and 1.4, 1.6, and 1.9, respectively, over sea. Therefore, diurnal fluctuations in positive LCCG lightning ratios decreased over land and increased over sea with an increase in peak-current threshold.

4. Discussion

The analysis in this study has exposed distinct differences between the properties of SCCG and LCCG lightning (section 3a) and their spatial and temporal distributions (sections 3b and 3c). Previous studies have suggested mechanisms to explain the large peak current of lightning in particular situations.

a. Mechanism associated with the underlying Earth's surface

Some authors have proposed that the higher conductivity of saltwater, which decreases the attenuation of an RS's radiation signal as it travels over the water surface, causes the peak current to be greater over the sea (e.g., Krider et al. 1996; Lyons et al. 1998). Tyahla and Lopez (1994) proposed that the initial charge on the lightning channel is transported more quickly on a surface with high conductivity; this causes a faster charge transfer and thus more energy discharge. The above theories are challenged by some observations that an abrupt change occurs in the negative peak current at the land–sea interface but not in the positive peak current (e.g., Orville and Huffines 2001; Orville et al. 2002). Furthermore, using observational evidence, Chronis (2012) found that there was a strong positive correlation between the NCG lightning median peak current (in absolute values) and salinity variability, but no clear trend for PCG lightning. If the decreased attenuation effect and the accelerated charge transfer effect of saltwater play a role, the effects should not be a function of polarity; in other words, PCG lightning and NCG lightning should show similar behavior in their land–sea variation of peak current. On the other hand, if the decreased attenuation effect works, sharp change in peak current along the land–sea interface should be replaced by gradual change.

Cummins et al. (2005) provided evidence that the first NCG RSs are enhanced over the ocean, unlike the first PCG return strokes and subsequent NCG strokes. They speculated that the enhanced NCG peak current could be attributed to a greater peak electric field uniquely associated with downward-propagating, negative-stepped leaders that attach to a smooth, highly conductive ocean surface. This explanation was partly supported by Said et al. (2013), who reported that land–sea boundaries for subsequent RS current were less pronounced than those for the first RS current. Nevertheless, the authors documented that there was still a noticeable enhancement of subsequent RS current across many land–sea boundaries, including along the western Mexican and Central American coastlines.

In contrast, some studies show lightning peak current geographical distributions that are quite different from typical situations (i.e., large peak current over the ocean, an abrupt change in peak current along the coastlines, and a distinct land–sea contrast for NCG lightning). For example, Chronis (2012) showed the land-based dominance of the PCG lightning peak over Greece. In the analysis of the lightning over South Africa, Gill (2009) found that the spatial distribution of NCG lightning did not display a pronounced discontinuity at the land–sea interface, and that a higher peak current occurred over sea than land for both NCG and PCG lightning. Orville et al. (2011) reported that PCG lightning along the West Coast of the United States also exhibited an abrupt change in peak current from land to sea; positive peak current along the West Coast were on the order of 40 kA or higher, while values were less than 30 kA inland along the coast of Northern California, Oregon, and Washington.

From this discussion, it is clear that we still do not well understand the effect mechanism of saltwater on the lightning peak current; all of the above theories might be reasonable but not cover all. Whatever the mechanism, it appears that at least the negative peak current over the global ocean are more prominent than over the continent (Said et al. 2013). We deduce that, in this study, the observation of a larger percentage of LCCG lightning over the sea than over land might be at least partly attributed to the impact of the underlying Earth's surface on estimated peak current, although the exact mechanism remains an open question. Next, we will focus on another mechanism associated with the intensity of thunderstorms.

b. Mechanism associated with thunderstorms

Chronis (2012) and Chronis et al. (2015) elaborated on the possible relationship between lightning peak current and thunderstorms. To put it simply, thunderstorms with stronger updrafts and more intense electrification have a
reduced breakdown electric field because of the greater concentration of charged hydrometeors (Petersen et al. 2008), and tend to feature pockets of opposite charge closer together because of the more turbulent mixing (Bruning and MacGorman 2013; Calhoun et al. 2013; Zheng and MacGorman 2016). This would cause more frequent lightning initiation and discharges, but less available charge for neutralization of the RS, which would result in a small peak current. In contrast, for relatively weak thunderstorms, the larger charge centers and thundercloud fields support larger peak current yields but low lightning frequency. This is indirectly supported by Chronis (2012), who reported a positive relationship between the lightning peak current and the time elapsed between lightning events, which means lightning with a large current would consume more charge and require a longer duration for recovery.

By using TRMM PF data to investigate the structure of precipitation systems with lightning discharge, we then examine the possible association of large peak current with convection intensity. To exclude the impact of the underlying Earth’s surface, we fix the analysis area to a rectangular region over land (shown in Fig. 1) that includes the zone with most frequent lightning flashes. Two analysis intervals are chosen: from 0000 to 0800 LT, when the ratio of LCCG lightning to the CG lightning is large over land, and from 1200 to 2000 LT, when the ratio is small over land (see Fig. 9b). PFs were chosen for analysis if they were accompanied by LIS flash records with geographical latitude and longitude centers located within the study area. A total of 100 PFs from 0000 to 0800 LT and 360 PFs from 1200 to 2000 LT were ultimately obtained. Four proxies are chosen to express the PF convection intensity: vertical profiles of maximum reflectivity, vertical profiles of the ratio of ≥40 to ≥20 dBZ areas (for investigating the height distribution of the convective component in total precipitation), the maximum height of the 20-dBZ echo, and the flash density relative to the convection area. The comparison of these proxies during the two time intervals is shown in Fig. 10.

All proxies in Fig. 10 suggest that the thunderstorms during 1200–2000 LT generally featured stronger convection than those during 0000–0800 LT. In addition, Fig. 10d further indicates that, for the same convection area, storms during 1200–2000 LT were more likely to produce a larger number of lightning flashes than those during 0000–0800 LT. These results, combined with the diurnal variation in LCCG lightning ratios (Fig. 9b), proposed that relatively weak storms tended to produce a higher percentage of LCCG lightning, while strong storms tended to produce more frequent lightning discharge but a lower percentage of LCCG lightning. The results shown in Fig. 10d may support the concept of pocket charges in storms with strong convection (Bruning and MacGorman 2013; Calhoun et al. 2013; Zheng and MacGorman 2016); that is, stronger convection tends to result in more pocket charges that cause more frequent lightning activity per unit area.

The precipitation region area is shown in Fig. 11a, and the ratio of the stratiform to precipitation areas is shown in Fig. 11b during 0000–0800 and 1200–2000 LT. Thunderstorms during 0000–0800 LT were more likely to have greater average horizontal extensions and stratiform regions. Large cloud areas, and especially large stratiform areas, might contribute to horizontal spreading of the charge, and hence to the formation of large horizontally orientated charge regions featuring long-propagation lightning flashes (Carey et al. 2005; Bruning and MacGorman 2013; Zheng and MacGorman 2016). According to Chronis et al. (2015), a continuous charge over a large area might cause large thundercloud fields and large peak current per CG lightning while the CG lightning frequency is low. This suggestion is supported by new work (Wang et al. 2016, manuscript submitted to Atmos. Res.). Based on 10 MCSs, Wang et al. found that median peak current in the first RSs of PCG and NCG lightning in the stratiform region were 26% and 24% greater than their counterparts in the convective region, respectively. Therefore, Figs. 10 and 11 propose that the thunderstorms with relatively weak convection and large precipitation size are more likely to produce LCCG lightning.

c. Association between positive LCCG lightning and MCSs

Lyons et al. (1998) and Pinto et al. (2009) both proposed an association between positive LCCG lightning and MCSs, although they did not give the direct evidence. Because the ratio of positive LCCG lightning is high during 0000–0800 LT (although the peak was at 0900 LT) and low during 1200–2000 LT (See Fig. 9c), Figs. 10 and 11 also suggest a relationship between positive LCCG lightning and large-area thunderstorms from the perspective of diurnal variations in lightning activity.

Next, we examine the association between geographical patterns during different seasons. Following the area threshold of MCS-type PF used in Luo et al. (2013), PFs accompanied by LIS flash records and with areas larger than 1000 km² were considered to be MCS-type PFs, and those accompanied by lightning with an area smaller than 1000 km² were considered to be sub-MCS-type PFs.

Figure 12 shows the geographical distribution of the frequency of MCS-type PFs over the study region during the rainy (Fig. 12a) and nonrainy seasons (Fig. 12b), with the frequency being calculated from grid sizes of 0.5°.
Comparing Fig. 12a with Fig. 6a, it appears that the spatial association between the high density of positive LCCG lightning and the high-frequency MCS-type PFs was weak during the rainy season. But, there is a more distinct relationship between positive LCCG lightning and MCS-type PFs during the nonrainy season. In this season, an area of high-frequency MCS-type PFs was located to the north of the analysis region (Fig. 12b), where there was also a high density of positive LCCG lightning (Fig. 6c) and a large ratio of positive LCCG lightning (Fig. 8d). At the same time, there was no apparent spatial correspondence between MCS-type PFs and positive SCCG lightning (refer to Figs. 5c and 8b) and between MCS-type PFs and negative LCCG lightning (Fig. 6d). Hence, the analysis suggests a positive relationship between positive LCCG lightning and MCSs, especially during the nonrainy season.

The association between positive LCCG lightning and MCSs may be partly attributed to the preference of PCG lightning for the stratiform region of MCSs (e.g., Goodman and MacGorman 1986; Rutledge and MacGorman 1988; Rutledge et al. 1990, 1993; Carey et al. 2005; Zheng et al. 2010), while the stratiform area provides good charge conditions for large-current discharge. This is supported by Petersen and Rutledge (1992), who found that the magnitude of the peak current of PCG
lightning increased with the growth of the stratiform region, and peaked when stratiform regions were most intense.

5. Conclusions

In this paper, we used GDLLS data from 2001 to 2013 to produce the first climatological comparison of SCCG and LCCG lightning over southern China. TRMM PF data were also used to discuss the association between LCCG lightning and convective precipitation systems. Our results show a distinct contrast between the properties of SCCG lightning and LCCG lightning, and their geographical distribution and diurnal variation. These properties change with season and also depend on the underlying Earth’s surface.

The percentage of LCCG lightning from total CG lightning was much greater over the sea than over land. Relative to SCCG lightning, LCCG lightning was slightly more likely to be positive. Furthermore, the percentage of positive LCCG lightning during the nonrainy season was more than twice that during the rainy season. However, the percentage of positive SCCG lightning showed only small seasonal differences. A PCG lightning flash was more likely to feature a large peak current than a NCG lightning flash, especially during the nonrainy season and over land. Meanwhile, the percentages of SCCG lightning from PCG and NCG lightning were similar.

There were distinct geographical differences between SCCG and LCCG lightning densities, as well as between the density distribution of positive and negative discharges within these types. The geographical distribution of the same-type or same-polarity CG lightning was different for rainy and nonrainy seasons. The geographical distributions of the ratio of PCG lightning from SCCG lightning were roughly similar in the rainy and nonrainy seasons, whereas the ratios of PCG lightning from LCCG lightning exhibited distinctly different geographical distributions from those in SCCG lightning, and also differed between rainy and nonrainy seasons.

In terms of diurnal variations, SCCG and LCCG lightning flashes over land both peaked at 1600 LT, while those over sea had two peaks: one in the morning and the other in the afternoon. However, the main peak in SCCG lightning occurred in the afternoon, while the main peak for LCCG lightning occurred in the morning. This caused a larger LCCG lightning ratio in the morning than...
in the afternoon. On the other hand, the percentage of positive SCCG lightning peaked in the morning, and was lowest in the afternoon over both land and sea. However, the percentage of positive LCCG lightning had a morning peak over land and an afternoon peak over the sea. Furthermore, with the increase in the peak-current threshold, the diurnal fluctuations in the percentage of positive LCCG lightning decreased over land but increased over the sea.

In terms of diurnal variations of LCCG lightning and structures of TRMM PFs with LIS flash observations, it was found that thunderstorms with relatively weak convection and large precipitation areas were more likely to produce LCCG lightning. Furthermore, active positive LCCG lightning was associated with large-area MCS-type PFs, and this was particularly evident in the spatial distribution during the nonrainy season. This might be attributed to the preference of positive LCCG lightning in the stratiform regions of MCSs.

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REFERENCES


Xu, W., 2013: Precipitation and convective characteristics of summer deep convection over East Asia observed by TRMM. Mon. Wea. Rev., 141, 1577–1592, doi:10.1175/MWR-D-12-00177.1.


